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Product modularity and its effects on the manufacturing firm

A contingency perspective

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PRODUCT MODULARITY AND ITS EFFECTS ON THE MANUFACTURING FIRM

A CONTINGENCY PERSPECTIVE

BY
HENRIKE E. E. BOER

DISSERTATION SUBMITTED 2016

AALBORG UNIVERSITY
DENMARK

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Dissertation submitted

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ENGLISH SUMMARY

To draw attention to a phenomenon that attained increasing attention in industry and academia, early works in the product modularity literature promoted the concept as a way of achieving sustained competitive success in an environment, dictated by heterogeneous markets, sophisticated customers, aggressive international competition and shortened product lifecycles. These early works presume that product modularity will enable the firm to more efficiently organize their manufacturing and product development tasks, and, in effect, improve firm performance. In particular, by standardizing modules and module interfaces, modularity is proposed to enable late-point differentiation, where standard components are manufactured-to-inventory and combined with variable components according to customer orders. Standardization of modules enables initial production and subassembly processes of these modules to be conducted according to mass production principles, resulting in economies of scale advantages and learning curve effects. Standardization of interfaces increases market responsiveness and product flexibility by enabling the firm to mix-and-match the final product according to specific customer demand. Standardization of interfaces is also key in the presumed link between product modularity and the organization of product development tasks. The creation of rules dictating how the modules are to interact (interface standardization) ensures that key information about the individual modules is codified and externalized. This enables a modular organization of tasks, where module-level design activities can be conducted concurrently by independent design units, while communication between these units can be restricted to key product information embedded in the component interfaces.

Early modularity research had a strong tendency to adopt a positive outlook on modularity, proposing potential performance effects without outlining whether these benefits are universal or context-specific. Currently, modularity research is in a phase where these enthusiastic propositions are put under scrutiny using empirical evidence. In line with this research, this thesis uses survey research to explore how modularity influences the performance of manufacturing firms from a contingency perspective, focusing not only *what* performance effects manufacturing firms can expect from increasing the level of modularity of their product portfolio, but also *how* these effects are achieved. Therefore, the purpose of this thesis is to investigate how organizational practices and context affect the association between product modularity and the performance of manufacturing firms.

The findings suggest that the external environment does indeed affect the applicability of modularity. Firms are more inclined to pursue modularity when they have products of a more complex nature, and experience more customer heterogeneity, higher rates of technological change, larger market growth, and more intense competitive rivalry. Based on these findings, I suggest the technological rates of change and market demands for customization to be primary pressures driving the adoption of modularity by affecting the value a firm can achieve by pursuing the practice, whereas competitive rivalry and market growth are factors creating urgency, impacting the likelihood that firms will react to these pressures.

Conforming to the findings of other survey research, the results of the thesis indicate that modularity has a positive influence on cost/speed, quality, flexibility, delivery and service performance. More specifically, modularity is found to be associated with lower manufacturing unit and purchasing costs, higher mix and volume flexibility, increased product customization, faster delivery speed, more reliable delivery, better customer service quality, and increased product assistance and support capability.

The thesis adds to existing survey research by ascertaining two ways in which modularity influences performance. First, the data suggest that the position of the customer order decoupling point influences the performance effects firms achieve through modularization. Modularity in assemble-to-order environments leads to better processing related performance (i.e. increased delivery and procurement speed, lower manufacturing unit and ordering costs), whereas firms that manufacture-to-order become more responsive to customers (through increased volume and mix flexibility, product customization, product assistance and customer service quality). In addition, DTO manufacturers also benefit from implementing modularity; DTO that adopt modularity to a high degree perform significantly better in terms of introduction ability, service quality, ordering costs and procurement lead time than firms with low levels of modularity. Second, the data confirms that integration plays an important role in (partially) mediating the modularity-performance relationship. Modularity not only influences cost/speed, quality, delivery, flexibility and service performance directly, it also has indirect effects on performance through integration. Modularity is found to be a mechanism by which cross-departmental internal integration and external integration with suppliers and customers can be increased, which in turn increases operational performance in these areas.

DANSK RESUME

Med det formål at gøre opmærksom på et fænomen, der vakte øget interesse i både industrien og den akademiske verden, promoverede tidlige værker indenfor modulariseringslitteraturen konceptet som en måde hvorpå virksomheder kunne opnå vedvarende konkurrencefordele i et miljø præget af forskelligartede markeder, sofistikerede kunder, tiltagende international konkurrence og forkortede produktlivscyklusser. Disse tidlige værker antog at produktmodularisering muliggør en mere effektiv organisering af produktudviklings- og fremstillingsprocesser og derigennem øger virksomhedens ydeevne. Litteraturen foreslog at modularisering, gennem standardisering af komponenter og ensretning af grænseflader, ville sætte virksomheden i stand til at udskyde produktdifferentieringspunktet, hvor standardkomponenter produceres til et mellemvarelager og kombineres med variable komponenter på basis af kundeordrer. En øget standardisering af komponentgrupper sikrer at virksomheder kan opnå stordriftsfordele ved at benytte masseproduktionsprincipper i deres produktions- og montageprocesser og samtidig benytte den øgede stabilisering til at danne basis for indlæringskurveeffekter. Standardiserede grænseflader mellem komponenter forbedrer virksomhedens reaktionsevne og fleksibilitet idet virksomheden derigennem kan konfigurere en mangfoldighed af slutprodukter i henhold til specifikke kundekrav. Standardiserede grænseflader antages også at være det virkemiddel gennem hvilket modularisering påvirker organiseringen af produktudvikling. En ensretning af grænseflader betyder at der fastsættes regler for hvordan moduler skal interagere, hvilket indebærer en kodificering af kerneviden omkring modulerne og deres interaktion.. Dette understøtter en modulær organisering af produktudviklingsopgaver, hvor uafhængige enheder kan designe forskellige moduler parallelt og kommunikation på tværs af disse enheder kan fokusere på den information som er indlejret i grænsefladerne.

Tidlig forskning på modulariseringsområdet havde en tendens til at male et meget positivt billede af modularisering og foreslog mange forskellige fordele, uden at redegøre for hvorvidt disse fordele var universelle eller kontekstafhængige. På nuværende tidspunkt er modulariseringsforskningen på et stadie, hvor disse antagelser bliver udfordret ved hjælp af empirisk baseret forskning. I tråd med dette, bruger denne afhandling data fra spørgeskemaundersøgelser til at undersøge hvordan modularisering påvirker produktionsvirksomheden og dens præstationsevne. Inspireret af organisatorisk contingency teori, fokuserer afhandlingen ikke kun på *hvilke* effekter produktionsvirksomheder kan opnå via modularisering, men også på *hvordan* disse effekter opnås. Afhandlingens formål er derfor at undersøge hvordan organisatoriske praksisser og virksomhedens kontekst påvirker relationen mellem produktmodularisering og produktionsvirksomheders præstationsevne.

Resultaterne bekræfter at kontekstuelle faktorer påvirker anvendeligheden af modularisering i den enkelte virksomhed. Det er især virksomheder, der har en større produktkompleksitet og er udsat for en mere heterogen kundemasse, hyppigere teknologiske skift, højere markedsvækst og konkurrenceintensitet, der

anvender modularisering i et højere omfang. Da hyppigheden of teknologiske skift og markedskrav om kundetilpasning direkte påvirker den værdi virksomheden opnår gennem modularisering, opstiller jeg den tese at disse faktorer er primære drivkræfter bag virksomhedens tilbøjelighed til at anvende praksissen, hvorimod den grad af konkurrence og markedsvækst virksomheden oplever, påvirker sandsynligheden for at virksomheder vil reagere på eksterne krav.

I tråd med eksisterende forskning, viser afhandlingens resultater at modularisering har en positiv indflydelse på virksomhedens kosteffektivitet, kvalitet, fleksibilitet, leveringsevne og serviceniveau. Anvendelse af modularisering er forbundet med lavere produktions- og indkøbsomkostninger og større mix- og volumenfleksibilitet, højere leveringshastighed og -pålidelighed, bedre kundeservice og kundetilpasningsevne samt en bedre evne til at yde produktassistance og support. Afhandlingen bidrager til eksisterende forskning ved at klarlægge to måder hvorpå modularisering påvirker virksomhedens præstationsevne. For det første viser data at placeringen af kundeordre dekoblingspunktet har en indflydelse på, hvilke resultater virksomheden opnår gennem modularisering. Under montage-til-ordre resulterer brugen af modularisering i fremstillingsrelaterede effekter (i form af hurtigere levering og indkøb samt lavere produktions- og indkøbsomkostninger), derimod opleves under produktion-til-ordre i stedet kunderelaterede effekter ved brugen af praksissen (i form af højere volumen- og mixfleksibilitet og bedre kundetilpasningsevner, produktassistance og kundeservice). Ydermere, så kan modularisering også gavne virksomheder, der anvender konstruktion til ordre princippet, idet modularisering her er forbundet med bedre produktintroduktionsevne, servicekvalitet, samt lavere omkostninger og gennemløbstider i indkøb. Datasættet bekræfter også at integration spiller en vigtig rolle i relationen mellem modularisering og virksomhedens præstationsevne. Modularisering har ikke kun en direkte effekt på virksomhedens omkostninger, hastighed, kvalitet, fleksibilitet og service, men også en indirekte effekt gennem integration. Resultaterne indikerer at modularisering er en måde hvorpå virksomheden kan øge intern integration på tværs af afdelinger og ekstern integration med kunder og leverandører, og at denne øgede tværfunktionelle og tværorganisatoriske integration forbedrer virksomhedens præstationsevne indenfor de nævnte områder.

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CHAPTER 1. INTRODUCTION

Over the last many decades, there has been a gradual evolution in the mix of competitive dimensions that manufacturers pursue. Following the popularization of Japanese production practices in the late 1980s, firms moved beyond the mass manufacturers' traditional focus on economies of scale, to also incorporate quality and time considerations in search for new levels of manufacturing effectiveness (Bolwijn and Kumpe, 1990). By the beginning of the 1990s, firms also started to recognize the importance of a fourth competitive dimension, flexibility (Bolwijn and Kumpe, 1990). By then, the ability to provide a wide range of customizable products had become an important competitive parameter in many industries (Pine, 1993; Da Silveira, 1998; Scavarda *et al*., 2010). To be able to achieve new levels of flexibility, without sacrificing cost, quality or time performance, researchers have proposed product modularity as one of the potential solutions.

Modularity is an attribute, which has been used to describe numerous objects, including knowledge, processes, work structures, organizations, and supply chains. This thesis is about modularity in assembled products, i.e. product modularity. Product modularity refers to a design philosophy aimed at enabling manufacturers to mix-and-match standardized components according to individual customer needs. Modularity enables the effective use of modules in *multiple* products. It is therefore not the property of a single product, but rather the property of a set of products, i.e. one or more families or even generations of products.

Product modularity builds on two principles: the standardization of modules and the standardization of interfaces. One way of creating standardized modules is by ensuring that there is a similarity between the physical and functional architecture of the overall system design, so that (a set of) components can be identified or designed that can perform the same function in several products. To ensure that modules can be used across different products also requires the creation of clusters of components that are internally interdependent but independent from the components external to the modules. These clusters of components can be identified by mapping the overall system architecture, which means identifying the interdependencies and relationships between the constituent parts and components and clustering those components that are highly interdependent. The dependencies between the resulting modules are then reduced or eliminated by creating standardized interfaces/ specifications for how the modules are to interact. These specifications standardize, amongst others, the spatial and geometrical interactions as well as the materials, energy and information exchange between the components.

Standardization of modules and interfaces facilitates the production and sub-assembly of standardized components according to traditional mass production principles, whereas the final product can be quickly configured and assembled once customer requirements are known, thus combining cost-efficient production with increased product flexibility (mix, change-over, and modification flexibility) and greater market responsiveness. The increase in component sharing between product variants and generations enables firms to achieve typical economies of scale advantages combined with learning curve effects, resulting in continuous improvements in manufacturing speed, costs and quality. Moreover, by standardizing the interfaces between components, modularity allows firms to focus their innovative efforts on one part or subsystem without having to take the overall product design into consideration. Consequently, modularity enables firms to develop products faster and more frequently. The implementation of product modularity, thus, presents a way in which firms can improve their operational performance – combining increased lower costs with better quality, speed, flexibility and innovation performance.

Even though modularity has been claimed to have a positive effect on these performance areas, more empirical research is needed to verify these effects and detail the causes and nature of these effects. The purpose of this thesis is, therefore, to examine product modularity and its performance effects on the firm, and identify and discuss important contingencies that influence the strength and nature of these effects. More specifically, the overall research objective of the thesis is to examine the question:

"How does product modularity influence the performance of manufacturing firms?"

Not all organizations can expect (the same) benefits from using product modularity. More specifically, I reason that the strength and nature of the performance effects of using product modularity in the manufacturing firm depends to a large degree on its internal and external context. Product modularity is not a one-size-fits-all solution, and the effects and effectiveness of using product modularity are a result of its "fit" with certain internal and external organizational characteristics, including the firm's competitive environment and market place, work arrangements, and practices employed during manufacturing and product development. Therefore, this thesis not only provides empirical evidence that identifies *what* operational performance effects firms experience when adopting modularity, but also embraces practices and contextual contingencies that influence *how* product modularity affects performance.

1.1. CONTENTS

In essence, this PhD thesis builds upon a collection of papers later revised or added to (summarized in Table 1). These papers will be referred to throughout the thesis, as paper 1, paper 2, and so forth. Not only do the papers highlight the particular areas of interest in this PhD thesis, they indicate the development the research has undergone.

Table 1 - Summary of papers

Paper 1: Product modularity and its effects on firm performance **Operationalization and measurement**
Method: Literature review - Subject search for journal articles in four databases. **Purpose:** To operationalize product modularity and firm performance. The paper starts off with finding researchable areas in the modularity literature, concluding that an operationalization of modularity is needed to support future research into the effects of modularity on firm performance. It then discusses the measures and characteristics used in the literature to portray modularity, based on which the paper proposes modularity to be measured using two product characteristics, i.e. the degree of interface standardization and the degree of module standardization in the product portfolio. Based on a review of existing literature, the paper concludes that in order to get a more detailed understanding of how modularity influences firm performance, items are needed that measure performance on the level of the manufacturing and product development processes.

Paper 2: Product, organizational, and performance effects of product modularity
Method: Extended literature review – Subject search in four databases and snowballing. **Purpose:** To operationalize and link product modularity to firm performance. Based on a review of measures used in and findings of existing survey research in modularity, the paper concludes that there is a need for combining and clarifying what the literature proposes the effects of product modularity on firm performance to be. To do so, the paper delineates between *characteristics of modularity* (standardized component interfaces, standardized components and dedicated functions), the *effects of modularity on product level* (product decomposability, less complex final assembly, component carry-over and commonality, combinability and independence), the *effects of modularity on organizational level* (focused production, parallel product development and postponement) and *performance effects of modularity* (including learning curve effects, economies of scale, and short and long term effects on innovation).

Paper 3: Contrasting platform thinking and product modularization **A survey of Swedish product development practices**
Method: Survey research – Independent sample t-tests based on data collected through a survey of Swedish development practices. **Purpose:** To examine the context in which the combined or separate use of the product modularization and platform thinking is appropriate and find the types of product development practices that compliment these approaches. The paper introduces and contrasts two approaches – product modularization and platform thinking – and identifies contingencies and complementary practices that might affect the adoption of these approaches. Based on the survey data, the paper finds that firms with a high use of product modularization have customers that specifically value customization and that these firms often employ modularization together with quality function deployment, design for assembly, failure mode and effects analysis and technological readiness level classification. Firms that use platform thinking experience lower rates of technological change, have a more formalized product development organization, use defined gates and/or goals and technology readiness level classification, and conduct a significantly lower amount of outsourcing of their product development work.

(Continued on next page)

Table 1 continued - Summary of papers

Paper 4: Design for Variety, postponement and operational performance
Method: Survey research – Independent sample t-tests based on data collected through the 6th International Manufacturing Strategy Survey. **Purpose:** To address the question whether the position of the CODP affects the performance effects of design-for-variety practices and, if so, how? The paper first introduces design-for-variety (DFV) practices (such as standardization, modularization, using product platforms, design for assembly and design for manufacturing), which are practices that focus on reducing variety-induced costs by capitalizing on commonality between components and products. It comments on which performance effects can be expected from DFV practices and posits that some of these effects are contingent on the customer order decoupling point (CODP). Based on the survey data, the paper concludes that the effects on DFV on product introduction and quality performance are largely independent on the CODP, whereas the performance effects of modularization on flexibility, delivery, service, cost and time performance are not. Firms that manufacture- or assemble-to-order are capable of reaping most benefits from DFV practices.

Paper 5: The impact of Design for Variety on operational performance: Mediation by internal, supplier and customer integration
Method: Survey research – Mediated regression based on data collected through the 6th International Manufacturing Strategy Survey. **Purpose:** To determine which type(s) of integration mediate the relationship between the use of design-of-variety practices and performance. The article reviews 30 works which, using survey data, investigate the performance effects of DFV practices (including the effects of individual practices such as platform thinking, product modularity, design for assembly and design for manufacturing). Existing survey research confirms that the use of these practices has an overall positive effect on both financial and operational performance, but does not agree on or elaborate how DFV influences specific operational performance dimensions. The research also agrees that integration constitutes an important mechanism by which DFV practices influence performance, but does not agree whether integration is a predecessor, a moderator or a mediator in the DFV-performance relationship. Based on survey data, the article concludes that integration plays a prominent role as a partial mediator in the relationship between DFV and performance. It finds that the use of DFV practices has a positive effect on quality, flexibility, service, delivery and cost/speed performance. The article adds that some of these effects can be explained by the fact that the use of DFV practices supports cross-functional and cross-boundary integration, which in turn is reflected in better operational performance.

The main body of the thesis follows the same overall logic as the papers. In order to grasp the overall field of modularity research, it starts off with a theoretical exploration of the field to find and choose an area pertinent for further research, and also provides the background for a conceptual clarification of the term modularity (cf. Paper 1). Inspired by contingency research, the thesis then defines modularity, explores the performance effects of product modularity reported in the literature and identifies contextual characteristics and organizational practices that might influence the appropriateness and effects of product modularity (cf. Paper 2). Then, survey data is used to test a) in which contextual settings the use of modularity is prevalent,

b) the performance effects of modularity, and c) how certain practices influence the modularity-performance relationship (cf. Paper 3-5).

The thesis is divided into three separate parts. Chapter 2, 3 and 4 constitute the theoretical underpinnings of the thesis, and explore the effects of product modularity on the manufacturing firm from a theoretical angle. To substantiate the need for researching the effects of modularity from a contingency perspective, the thesis starts off with an analysis of the development of research in the modularity field during the last 50 years and identifies both established and less mature research areas within the modularity literature (Chapter 3). Chapter 2 describes how the modularity literature for this analysis has been identified and selected. Since modularity is used for widely different applications and researched from many different angles across many different research streams, Chapter 4 clarifies how modularity is viewed and defined in this thesis. Chapter 4 also sets modularity in a wider context. It identifies how product modularity can be expected to influence the manufacturing firm and which contextual factors and practices might influence this relationship.

The second part of the thesis introduces the research method applied in the thesis. Chapter 5 introduces the thesis' three sub-objectives and describes the survey research conducted to accommodate these objectives. It familiarizes the reader with the three surveys that provide the empirical background for the thesis, describes the data collection methods applied and the resulting samples, and details the measurement instrument used to collect the data.

The findings of this survey research are presented in Chapter 6. Chapter 7 then contrasts these findings against existing research, pinpoints areas for further research and discusses the limitations of the thesis. Chapter 8 concludes the thesis; it summarizes how existing modularity research has influenced the choice of research objective, specifies the main findings and the theoretical contribution of the thesis, and recapitulates important areas for further research.

CHAPTER 2. THEORETICAL UNDERPINNINGS

Research into modularity has expanded greatly over the past decades. Not only is the concept used for widely different applications, it has been researched from many different angles across many different research streams and even scientific disciplines. Promoted as being able to bridge the trade-off between achieving high end-product variety and low manufacturing costs, product modularity is believed to play a central role in mass customization and variety management. Based on a number of success stories, researchers have been promoting this concept as an important piece in the puzzle of achieving or sustaining competitive success in an environment, which is dictated by heterogeneous markets with increasingly sophisticated customers, a growing number of aggressive, international competitors, and shortened product life cycles (Wheelwright and Clark, 1992; Pine, 1993; Magnusson and Pasche, 2014). Whether or not product modularity really is all that it is suggested to be, interest in the concept has spurred a wide array of researchers to make their contribution to this field. Not surprisingly, this has made the field of modularity an intricate area of research, difficult to grasp in its entirety for an experienced researcher, let alone an inexperienced PhD fellow. Therefore, the PhD process not only started with but also ended with an intensive literature study to find the most prominent articles that give insight into the concept of product modularity and its effects on the manufacturing firm.

The survey of existing literature conducted during the initial phases of the PhD research was aimed at 1) providing an overview of researched and researchable problems in the modularity field, 2) aiding in the conceptual clarification of the term modularity and 3) identifying how modularity can be expected to influence firm performance. To do so, a two-stage process was followed. First, a subject search was conducted to find journal articles that operationalize modularity and/or examine product modularity and its effects on firm performance (Literature review 1: Paper 1). This first step resulted in a total of 25 journal articles. In order to find the most influential authors within the modularity literature, the second step in the literature review examined the references of these original journal articles, resulting in an additional 21 articles, books, or papers (Literature review 2: Paper 2). To facilitate the survey research conducted during the later phases of the PhD research, an additional literature review was conducted close to the end of the PhD process, to find all articles that study the effects of modularity based on survey data (Literature review 3: Paper 5). This search added 15 papers to the pool. Additionally, 22 references emerged in the process of writing the papers.

To revise and add to the findings based on the original set of literature reviews and get a better understanding of the development modularity research has undergone, a final literature review was conducted to support the analyses and discussions presented in this thesis.

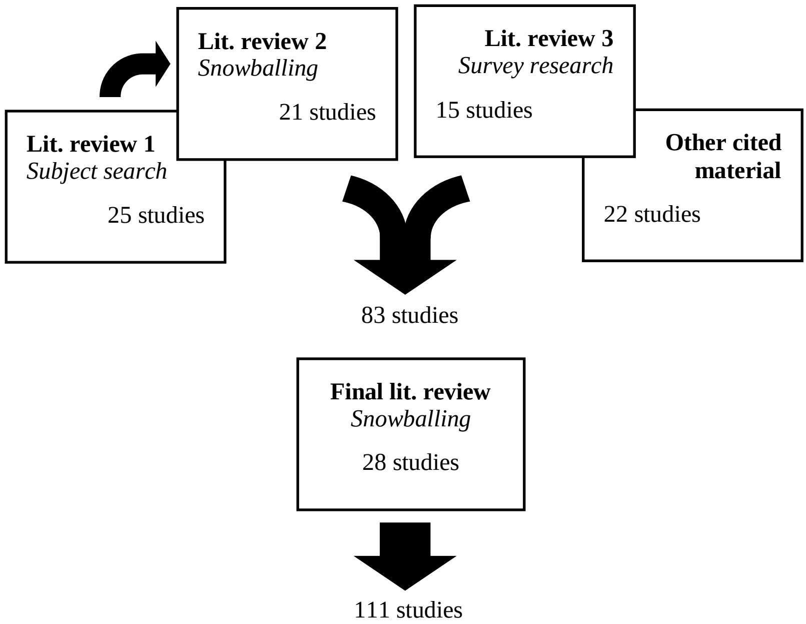

Figure 1 - Final literature review

To fully understand the theoretical underpinnings of the PhD thesis, this final literature review encompasses all 83 studies addressing modularity found in any of the three literature reviews or referenced that emerged during the process of writing the papers. Based on the list of references of these 83 studies, 28 additional works were added to the pool of literature. These 28 works were considered of importance, as these are referenced to eight times or more by the other 110 papers part of the final literature review. The resulting 111 studies constitute the main body of reference for this thesis. Figure 1 illustrates the entire literature search process.

The review is confined to articles and books discussing the implications of product modularity (or similar concepts) for manufacturing firms, as well as articles that have taken a very prominent role in influencing the modularity literature. As a result, many articles that, for instance, primarily aim at developing and testing modularization methods are excluded. Additionally, some articles are excluded from the literature base, not because they are not highly cited, but represent general theories widely used in almost every branch of existing organizational research (such as Barney, 1991; Mintzberg, 1979; Prahalad and Hamel, 1990; Schumpeter, 1942; Williamson, 1985) or concern methodology and data analysis (such as Eisenhardt, 1989; Hair *et al*., 2009; Yin, 1994).

Table 2 - Overview of the literature review

Core	Referenced more than 20 times
B Baldwin and Clark, 1997	B Sanchez, 1995
B Baldwin and Clark, 2000	B Schilling, 2000
B Garud and Kumaraswamy, 1995	B ***Simon, 1962***
B ***Henderson and Clark, 1990***	B Ulrich and Eppinger, 1995
B ***Meyer and Lehnerd, 1997***	B Ulrich and Tung, 1991
B ***Pine, 1993***	B Ulrich, 1995
B ***Robertson and Ulrich, 1998***	E Langlois and Robertson, 1992
B Sanchez and Mahoney, 1996	

Highly cited	Referenced between 11 and 20 times
A Gershenson *et al*., 2003	E ***Alexander, 1964***
A Worren *et al*., 2002	E ***Clark, 1985***
B ***Clark and Fujimoto, 1991***	E Duray *et al*., 2000
B Sanchez, 1999	E Feitzinger and Lee, 1997
B ***Sanderson and Uzumeri, 1995***	E ***Fisher et al., 1999***
B Starr, 1965	E ***Kotha, 1995***
B ***Wheelwright and Clark, 1992***	E ***Meyer and Utterback, 1993***
D ***Fine, 1998***	E ***Pine et al., 1993***
D Garud and Kumaraswamy, 1993	E Sanchez, 1996
D ***Orton and Weick, 1990***	E Schilling and Steensma, 2001
D Salvador *et al*., 2002	E ***Von Hippel, 1990***

Cited	Referenced 5 to 10 times
A Jacobs *et al*., 2011	E Ernst and Kamrad, 2000
A Lau *et al*., 2007a	E ***Evans, 1963***
A ***Muffatto, 1999***	E Galvin and Morkel, 2001
A Pil and Cohen, 2006	E ***Lampel and Mintzberg, 1996***
B Brusoni and Prencipe, 2001	E Langlois, 2002
B Ethiraj and Levinthal, 2004	E ***Meyer et al., 1997***
C Tu *et al*., 2004	E Mikkola, 2003
D ***Abernathy and Clark, 1985***	E ***Nobeoka and Cusumano, 1997***
D Erixon, 1996	E ***Novak and Eppinger, 2001***
D Ernst, 2005	E ***Parnas, 1972***
D Karmarkar and Kubat, 1987	E Ro *et al*., 2007
D Mikkola and Gassmann, 2003	E Salvador, 2007
D Mikkola, 2006	E Sanchez and Collins, 2001
D ***Sawhney, 1998***	E Sanchez, 2000
D Sosa *et al*., 2004	E ***Utterback, 1994***
E ***Clark, 1989***	

(Continued on next page)

Table 2 continued - Overview of the literature review

Few or no citations	Referenced less than 5 times
A Arnheiter and Harren, 2006	C Jacobs *et al*., 2007**
A ***Bierly III et al., 2008***	C Lau *et al*., 2007b**
A Chung *et al*., 2012	C Lau *et al*., 2009
A Danese and Filippini, 2010	C Lau *et al*., 2010**
A Danese and Filippini, 2013	C Lau *et al*., 2011
A Duray, 2004	C Liao *et al*., 2010
A Eom, 2008	C Parente *et al*., 2011
A Ethiraj *et al*., 2008**	C Salvador and Villena, 2013
A Ethiraj, 2007**	C Thatte, 2013
A Genba *et al*., 2005	C Vickery *et al*., 2015
A Guo and Gershenson, 2007	C Zhang *et al*., 2014
A Kamrad *et al*., 2013	D ***Baldwin and Woodard, 2009***
A Morris and Donnelly, 2006	D Campagnolo and Camuffo, 2010**
A Muffatto and Roveda, 2002**	D Chesbrough and Kusunoki, 2001**
A ***Pasche and Sköld, 2012***	D ***Da Silveira et al., 2001***
A ***Pasche et al., 2011***	D ***Halman et al., 2003***
A Watanabe and Ane, 2004	D Magnusson and Pasche, 2014
C Ahmad *et al*., 2010	D Marshall *et al*., 1998
C Bush *et al*., 2010	D Persson and Åhlström, 2006
C Droge *et al*., 2012	D Pil and Holweg, 2004**
C Hao *et al*., 2015	D ***Ramdas, 2003***
C Howard and Squire, 2007**	

Legend

A From first literature review
B From second literature review
C From third literature review
D Referred to in one of the five papers
E Added during final literature review
** Cited 50 times or more in Google Scholar

Table 2 provides an overview of these 111 articles. First of all, it divides the literature into two groups: one group contains works that directly address modularity, the other group consists of adjacent research that does not primarily focus on introducing, promoting or defining product modularity, but played a fundamental role in shaping modularity research (in bold and italics). It also divides the literature into four different groups based on the number of times the respective work has been referenced to by the other 110 articles.

'Core' studies are articles and books referred to more than 20 times, 'highly cited' studies are referred to between 11 and 20 times, 'cited studies' are referred to 5 to 10 times, and the remaining group of studies are those that have been cited four times or less by the other works in the literature pool. Moreover, the table indicates whether the respective work is from the first literature review (A), the second literature review (B), the third literature review (C), has been referred to in one of the five papers (D) or was added to during the final literature review (E).

The next chapter uses the literature reviews to provide insight into how and why modularity research has developed as it has, and assesses the current maturity of the field. It does so by taking outset in the most influential works in the modularity field. Therefore, the analysis of how modularity research has developed over the past 50 years is limited to 50 studies. Forty of these studies are viewed fundamental in this analysis as they are referenced to at least 5 times by the other studies of the final literature review. Ten of these studies are referred to less than 5 times by the other studies part of the literature review, but are added as they are cited 50 times or more by Google Scholar (indicated by ** in Table 2). The analysis of the adjacent research is confined to 26 books and articles, and includes only studies that have been cited eight times or more by the other studies part of the final literature review.

CHAPTER 3. CHOICE OF RESEARCH DIRECTION

The purpose of this chapter is to provide an overview of potential research directions within the modularity literature, and to substantiate the need for research that addresses the effects of modularity on manufacturing firms from a contingency perspective. In order to identify and discuss these research themes, this chapter provides an overview of how modularity research has developed the past 50 years, and links modularity research to developments in adjacent research. First, however, the chapter discusses the history behind the terminology used within the modularity literature.

3.1. TERMINOLOGY

Many different terms, listed in Table 3, are used in the literature to describe and define product modularity, many of which are not new. One major source of inspiration behind modularity terminology was systems theory. One of the articles widely cited in the modularity literature is Simon's (1962) discussion of complex hierarchical systems. In that article, he introduces the concept of nearly decomposable systems, where "*the interactions between subsystems are weak but not negligible*" (p. 474) and "*intra-component linkages are generally stronger than inter-component linkages*" (p. 477), attributes often used to describe modularity. Similarly, Alexander (1964) states that in order to design forms that are well adapted to their context, the designer needs to organize his problem by developing a hierarchy of concepts. More specifically, the designer needs to create a set of simpler subsystems, which are internally richly connected but are as independent from each other as possible, as "*no complex adaptive system will succeed in adapting in a reasonable amount of time unless the adaptation can proceed subsystem by subsystem, each subsystem relatively independent of the others*" (Alexander, 1964, p. 41). Almost three decades later, Von Hippel (1990) also concludes that firms should arrange tasks to reduce the problem-solving interdependency between them in order to ensure the efficiency and effectiveness of innovation management. Creating this independency between subsystems constitutes the core of loosely coupled systems, which are systems that are both responsive *and* distinctive (Orton and Weick, 1990). These works on systems theory have greatly inspired the literature on modularity. From these works, the terms loose coupling, near decomposability, weak interaction or relative independency between subsystems often are used to describe the properties of modular design.

Modular programming also had a big impact on how modularity is defined in later works. Parnas (1972), for instance, introduces modularization as a way in which the flexibility and comprehensibility of a system can be improved, while development times can be reduced. Parnas uses well-known terms such as well-specified interfaces, information hiding, reassembly, and easy replacement of modules to describe efficient modular programming. More specifically, he argues that each task in the program should form a separate module, where modules are written with little knowledge about the code in another module (information hiding), have well-specified interfaces, which would allow modules to be assembled and replaced without having to reassemble the entire system.

Table 3 - Terms used to define and describe modularity

Term	Description	Used by….
Component sharing	The same components or subassemblies are used in a variety of products	*Worren et al., 2002; Tu et al., 2004; Lau et al., 2007a; Howard and Squire, 2007*
Component combinability	The underlying set of components can be mixed and matched to create different product configurations	*Starr, 1965; Feitzinger and Lee, 1997; Schilling, 2000; Salvador, 2007; Jacobs et al., 2011*
Loose coupling	Changes to a module do not trigger changes to other modules or components	*Ulrich, 1995; Ulrich and Eppinger, 1995; Sanchez, 1995; Sanchez and Mahoney, 1996*
Information hiding	Product design information is partitioned into visible design rules and hidden design parameters	*Baldwin and Clark, 1997; 2000*
Functional binding	The physical and functional architecture in the product exhibit high similarity	*Ulrich and Tung, 1991; Ulrich, 1995; Ulrich and Eppinger, 1995; Pil and Cohen, 2006*
Interface standardization	The way components interact is standardized	*Garud and Kumaraswamy, 1993, 1995; Sanchez, 1995; Sanchez and Mahoney, 1996*
Life cycle modularity	Components in the modules undergo similar processes and are independent of the processes of other components as they go through their lifecycle	*Gershenson et al., 2003; Campagnolo and Camuffo, 2010*
Independency	Components and parameters are interdependent within the modules and relatively independent across them	*Baldwin and Clark, 2000; Ernst, 2005, Ethiraj and Levinthal, 2004; Ethiraj et al., 2008*
Product separability	Modules can be built and designed independently and are easily detachable from the final product configuration	*Baldwin and Clark, 1997; Schilling, 2000; Salvador, 2007; Pil and Holweg, 2004*
Standard components	Use of components that have been used in previous or existing designs	*Mikkola and Gassmann, 2003: Mikkola, 2006, Lau et al., 2007a*

The notion of functional integrity, defined by Clark and Fujimoto (1991) as consistency between a product function and structure, is also used to characterize modular product architectures, which should exhibit "*one-to-one mapping from functional elements in the function structure to the physical components of the products* (Ulrich, 1995, p. 422).

3.1.1. SUMMARY - TERMINOLOGY

There is no consistent definition of modularity – many different terms have been used to describe the concept. Inspired by the systems theory literature, modular systems have been said to consist of independent modules that can be altered without having to change other components. Modular programming has inspired researchers to identify information hiding and interface standardization to be properties of modular systems. In addition, terms such as functional binding, component sharing, component combinability, standard components, product separability and life cycle modularity have also been used to describe modular systems.

3.2. THE DEVELOPMENT OF PRODUCT MODULARITY RESEARCH

Building on the work by Christensen (2006), who divides the process of building theory into two different stages, each with a set of iterative steps, I have categorized product modularity research into different groups or phases, dependent on the overall purpose of, and method applied in, the study considered. To ensure that this analysis of the development in modularity research only includes the most popular works, the analysis is limited to studies that have been cited five times or more by the other studies that are part of the final literature review, or have been cited at least 50 times by other articles in Google Scholar. Studies that do not directly address modularity but have been fundamental in developing modularity theory are analyzed in the Section 3.3 denoted 'adjacent research'.

3.2.1. ATTENTION-SEEKING

Even though the phases overlap to some extent, as shown in Figure 2, one group of studies stands out. This group, which I have denoted attention-seeking literature, involves studies that sought to draw attention to modularity as a phenomenon that attained increasing notice in industry and academia and, thus, provide the initial inspiration for instigating scientific research. The first author to draw attention to modularity in management research was Martin K. Starr, who noticed a new era in production management, wherein consumers were demanding ever-greater variety (Starr, 1965). As a solution, the author promoted modular production, i.e. "*capacities to design and manufacture parts which can be combined in numerous ways*" (Starr, 1965, p. 132).

Category	Up to 1996	1997-2001	2002-2006	2007-2011
ATTENTION-SEEKING	Starr, 1965 Ulrich and Tung, 1991 Ulrich, 1995 Ulrich and Eppinger, 1995	Baldwin and Clark, 1997 Baldwin and Clark, 2000		
EXPLORATION			Muffatto and Roveda, 2002 Gershenson et al., 2003 Mikkola and Gassmann, 2003 Mikkola, 2006	Salvador, 2007 Campagnolo and Camuffo, 2010
CONCEPTUAL THEORY DEVELOPMENT	Garud and Kumaraswamy, 1995 Sanchez, 1995 Erixon, 1996 Sanchez, 1996 Sanchez and Mahoney, 1996	Sanchez, 1999 Sanchez, 2000 Schilling, 2000 Chesbrough and Kusunoki, 2001	Langlois, 2002 Pil and Cohen, 2006	
THEORY DEVELOPMENT BASED ON CASE RESEARCH	Langlois and Robertson, 1992 Garud and Kumaraswamy, 1993	Feitzinger and Lee, 1997 Brusoni and Prencipe, 2001 Galvin and Morkel, 2001 Sanchez and Collins, 2001	Salvador et al., 2002 Mikkola, 2003 Pil and Holweg, 2004 Ernst, 2005	Ro et al., 2007
THEORY DEVELOPMENT BASED ON MODELLING	Karmarkar and Kubat, 1987	Duray et al., 2000 Ernst and Kamrad, 2000	Ethiraj and Levinthal, 2004	Ethiraj et al., 2008
THEORY TESTING			Schilling and Steensma, 2001 Worren et al., 2002 Sosa et al., 2004 Tu et al., 2004	Ethiraj, 2007 Jacobs et al., 2007 Howard and Squire, 2007 Lau et al., 2007a Lau et al., 2007b Lau et al., 2010 Jacobs et al., 2011

Figure 2 - Development in modularity research

However, as Starr predicted correctly, the concept did not come into being overnight, and modularity first truly gained interest again during the 1990s. Authors that played a prominent role during that time are Carliss Y. Baldwin and Kim B. Clark. Based on observations in the PC industry, these authors introduced and promoted modularity as a way of "*building a complex product or process from smaller subsystems that can be designed independently, yet function as a whole*" (Baldwin and Clark, 1997, p. 84), which requires the process of creating visible design rules and hidden design parameters, detailed in a subsequent book (Baldwin and Clark, 2000). Arguably even more significant authors are Karl Ulrich and his colleagues, who classified their work as preliminary research and "*more of a starting point than a set of refined conclusions*" (Ulrich and Tung, 1991, p. 1). They introduced and defined modularity as a product architecture that exhibits decoupled interfaces and a one-to-one correspondence between the functional and physical components, and contrasted this to an integral architecture, which exhibits function sharing within or across components and has ill-defined, incidental interactions between the primary components of the product. In addition, they identified potential costs and benefits of modularity, introduced different types of modularity and discussed what organizational implications modularity might have (Ulrich and Tung, 1991; Ulrich 1995; Ulrich and Eppinger, 1995).

3.2.2. EXPLORATION

Even though the authors that were part of the attention-seeking phase all provide their own definitions of modularity, there is a particular stream of research in the modularity literature, which has a more exclusive focus on developing our understanding of the concept, denoted exploration in Figure 2. Consistent with what Christensen (2006) calls 'observation' in his model of theory building, this area of modularity research is particularly interested in developing constructs and providing a more rigorous understanding of existing research. Some of the authors that are part of this stream of research even seek to operationalize modularity to such a degree that it is susceptible to measurement. For instance, Mikkola and Gassmann (2003) and Mikkola (2006) develop the modularization function, which uses information about the number of standard components in the product system, the number of interfaces per component, and the substitutability of new-to-the-firm components to analyze the degree of modularity in a given product structure. Another author seeking to operationalize modularity is Salvador (2007) who, based on an extensive literature review, defines a product system to be modular "*to the extent that its separable components, or modules, are combinable*" (Salvador, 2007, p. 229). He uses the two lower level constructs in his definition, i.e. component combinability and component separability, to arrive at a combinability index as a way to measure product system modularity.

In contrast to articles discussed so far in this section, the remainder of the articles categorized as being part of the exploration phase are less focused on developing a measurable definition of modularity. Instead, these articles aim at providing an overview of existing research and indicate areas for future research. Campagnolo and Camuffo (2010), for instance, divide modularity research into three different streams and identify incongruities and areas for further research within these streams. Gershenson *et al*. (2003) conduct an intensive literature review with the overall purpose to list and discuss the proposed benefits and existing definitions of modularity and indicate areas for further research. Even though these authors first and foremost seek to give an overview of product modularity research, they do provide some inputs as to how they believe modularity should be defined. In particular, Gershenson *et al*. (2003) conclude that the degree of modularity depends on whether the product has one or more modules that come close to the ideal module, which is a module that consists of "*components that are similar in the life-cycle processes they undergo, and independent from all components outside of the module as they go through their life cycle*" (Gershenson *et al*., 2003, p. 303).

3.2.3. THEORY DEVELOPMENT

Similar to Malhotra and Grover (1998), who divide survey research in exploratory and explanatory research, I divide the remainder of the modularity literature into two general domains: 1) the *theory development* domain, which suggests or proposes relationships between modularity and other constructs, and 2) the *theory testing* domain, which formalizes and tests these propositions. Theory development can be further divided into three groups, dependent on whether the research develops the theory based on anecdotal evidence and/or previous publications (conceptual theory development), case research, or modeling (see Figure 2).

Overall, the theory development phase in modularity research is characterized by an abundance of research interests. One example is Ron Sanchez, who is fundamental in developing the so-called mirroring hypothesis. The mirroring hypothesis holds that the use of modular products facilitates the firm to adopt modular processes and work structures. More specifically, the standard interfaces in the product design are believed to be crucial in providing embedded coordination that enables work to be conducted autonomously and concurrently (Sanchez, 1995; Sanchez and Mahoney, 1996). As a result, product modularity is said to enable firms to adopt modular production processes and a modular organization in product development, and will even help create an expanded network of modular development organizations (Sanchez, 1995; Sanchez and Mahoney, 1996; Sanchez, 1996; Sanchez, 2000). Throughout their articles, Sanchez and his colleagues propose that there is a great deal of benefits associated with using modularity in products, processes, knowledge and organizational design; it would help firms to, amongst others, conduct real-time market research, accelerate strategic learning, introduce new products more frequently, and achieve economies of scale (Sanchez, 1996; Sanchez, 1999; Sanchez and Collins, 2001). Like Sanchez, Garud and Kumaraswamy (1993, 1995) also promote modularity or, more precisely, modular upgradability. On the basis of an analysis of Sun Microsystem's open system strategy, the authors propose modular upgradability as a key to achieving economies of substitution, where "*technological progress can be accomplished by substituting only certain components of the multicomponent system while retaining others*" (Garud and Kumaraswamy, 1993, p. 362).

Not all authors are equally positive about modularity. A widely cited case study within the modularity literature is Feitzinger and Lee's (1997) study of mass customization at Hewlett Packard. This study also makes a compelling case for using modularity, as it identifies modular product designs, modular process designs and agile supply networks as basic building blocks behind an effective mass customization program. However, Feitzinger and Lee also argue that firms should carefully assess whether the benefits of standardization outweigh the added costs. Two articles that also are more cautious regarding the use of product modularity are Brusoni and Prencipe (2001) and Ernst (2005). Both articles question whether component interfaces can really provide all coordination needed within and across organizations and find that firms or networks developing modular products need more than standardized interfaces within the product design to achieve intra- and inter-organizational coordination. Similar to Chesbrough and Kusunoki (2001) and Ethiraj and Levinthal (2004), the two articles also conclude that the static nature of modular product architectures can have adverse effects on firm performance in the long run. Product modularity may slow down the rate of innovation (Ernst, 2005), make the firm less responsive to new technologies (Chesbrough and Kusunoki, 2001), make it difficult for the firm to manage fluctuating rates of change in their module base (Brusoni and Prencipe, 2001), or blind the designer from identifying effective new product configurations (Ethiraj and Levinthal, 2004).

The research themes detailed above represent just a fraction of the topics addressed in the theory development phase. Other authors develop theories that, for instance, discuss why systems move to a lower or higher degree of modularity (Schilling, 2000), examine the role of modularity in innovation and imitation deterrence (Pil and Cohen, 2006; Ethiraj *et al.*, 2000), study the effect of modularity in specific industries (Galvin and Morkel, 2001; Ro *et al.*, 2007), or examine the role of modularity in mitigating the effects of variety (Salvador *et al.*, 2002; Pil and Holweg, 2004).

3.2.4. THEORY-TESTING

The theory-testing phase in modularity research formalizes and tests hypotheses based on survey data, data from secondary sources or data collected through case research. Similar to the theory development phase, the theory-testing phase is characterized by diverse research directions. Schilling and Steensma (2001), for instance, test the logic of general systems theory (as proposed by Schilling, 2000), while Sosa *et al*. (2004) examine why misalignments between product architectures and organizational architectures occur. However, the majority of the articles within the theory-testing phase of modularity research test the effects of modularity on various performance dimensions. Another general theme within this survey-based modularity research is the relationship between product modularity, internal integration within the firm and external integration with customers and/or suppliers.

3.2.5. SUMMARY - THE DEVELOPMENT OF PRODUCT MODULARITY RESEARCH

To spur academic and practitioner interest, the initial works in modularity research focused on introducing and promoting this new concept. The early theory building researchers adopted the same positive outlook on modularity. Based on anecdotal and case evidence, product modularity was suggested to support economies of substitution and mass customization, and allow the firm to adopt a modular organization of product development work and to achieve wide range of performance benefits (Garud and Kumaraswamy, 1993; Garud and Kumaraswamy, 1995; Sanchez, 1995; Erixon, 1996; Sanchez, 1996; Sanchez and Mahoney, 1996; Feitzinger and Lee, 1997; Sanchez 1999; Sanchez, 2000). Around the turn of the century, the theory building research adopted a more nuanced perspective on the effects of modularity – researchers began examining the effects of modularity on performance more thoroughly (Ethiraj and Levinthal, 2004; Pil and Cohen, 2006; Ethiraj *et al*., 2008) and investigating if and how modularity mitigates the effects of product variety (Salvador, 2002; Pil and Holweg, 2004). Furthermore, they also started to question the assumption of a one-to-one relationship between product, organizational and market modularity (Langlois, 2002; Ernst, 2005). Recent modularity research also moved beyond very context-specific observations and test the implicit and explicit propositions developed in the previous phases based on larger-scale evidence. However, many of the propositions implicitly articulated in the attention-seeking and theory development phases have yet to be addressed fully.

3.3. ADJACENT RESEARCH

A wide array of books and articles have influenced how modularity theory has developed over the years. As mentioned, systems theory and modular programming have been the primary sources for inspiration behind the terminology used in modularity literature. However, there is also other research that has been fundamental in developing and contributing to the assumptions of the modularity literature, categorized in Table 4[1]. Common to these articles is that they are widely cited in the modularity literature, even though the articles have no primary focus on introducing, promoting or defining product modularity as such. This adjacent research can be divided into three main groups: a) literature that studies the effects of component sharing and product complexity on firm performance or inter-firm collaboration, b) literature that comments on the dynamics of innovation, and c) literature about mass customization or the use of product platforms.

3.3.1. EFFECTS OF COMPONENT SHARING

Given that many of the advantages of modularity derive from an increase in component sharing between different product variants; it is no wonder that the modularity literature is heavily inspired by other works studying the effects of sharing or using standard components and technologies between products and development projects. Evans (1963) is one of these works. It introduces the modular design problem by considering what features to include in a standard subsystem to be used across a product line from a mathematical angle.

[1]Only studies that have been cited eight times or more by the other studies part of the final literature review have been included in this analysis.

Table 4 - Themes in adjacent research

Terminology	Effects of component sharing	Innovation types and dynamics	Product platform	Mass customization
Simon, 1962: Nearly decomposable systems	Evans, 1963: Component sharing	Clark, 1985: Design hierarchies and technological evolution	Wheelwright and Clark, 1992: Product development and product platforms	Pine, 1993: Mass customization vs. mass manufacturing
Alexander, 1964: The process of design from a system perspective	Clark, 1989: The effects of project scope on product development performance	Abernathy and Clark, 1985: Architectural and other types of innovation	Meyer and Utterback, 1993: Product platforms and core capabilities	Pine et al., 1993: Mass customization and continuous innovation
Parnas, 1972: Modular programming	Nobeoka and Cusumano, 1997: Multi-project strategy in product development	Henderson and Clark, 1990: Architectural and other types of innovation	Sanderson and Uzumeri, 1995: Product platforms at Sony. The Walkman case	Kotha, 1995: Mass customization and mass manufacturing
Orton and Weick, 1990: Loosely coupled systems	Fisher et al., 1999: Performance effects of component sharing	Von Hippel, 1990: Task partitioning in innovation management	Meyer et al., 1997: Platform efficiency and effectiveness metrics	
Clark and Fujimoto, 1991: Product development and product integrity	Novak and Eppinger, 2001: Product complexity and vertical integration	Utterback, 1994: Dynamics of innovation and dominant design	Meyer and Lehnerd, 1997: Product platforms and product family planning	
		Fine, 1998: Clockspeed and temporary advantage	Robertson and Ulrich, 1998: Product platform planning	
			Muffatto, 1999: Platforms in product development	

Another prominent work is Clark's (1989) study of the effects different part strategies have on product development. By comparing European, Japanese and American firms, he concludes that Japanese firms have considerable advantages over American firms, partly due to the fact that Japanese firms have skilled supplier systems, capable of supplying unique components through black box design. Novak and Eppinger (2001), who also analyze the car industry in Japan, Europe and the U.S., add to this discussion by stating that product design complexity and vertical integration are complements. They suggest that simpler parts, such as modular, standard components with standardized interfaces, can be outsourced using financially separate suppliers, whereas more complex systems should be developed in-house or possible using *keiretsu* type partnerships. Based on an analysis of automotive front-brake sharing practices in 6 firms over an 11-year period, Fisher *et al*. (1999) discuss the trade-offs associated with increasing the degree of component sharing between products. Similar to key authors in the modularity literature (Ulrich and Tung, 1991; Ulrich, 1995), they find that component commonality can help firms achieve economies of scale in the production process. However, they also conclude that designing components to be used across multiple product lines may result in excess capability and cost penalties (Fisher *et al.*, 1999). Nobeoka and Cusumano (1997) also look at the effects of increased commonality, but focus on the effects of sharing components and critical technologies between product development projects rather than between products. They conclude that firms with rapid design transfer have a higher new product introduction rate and growth in sales. Similarly, product modularity is also often said to increase the rate to which firms introduce products (Baldwin and Clark, 1997).

3.3.2. INNOVATION DYNAMICS

A widely varied set of articles with a high impact on the modularity literature discusses which effects different types of innovation have on the manufacturing firm. Following the logic of Abernathy and Utterback's (1978) model of process and product innovation, these articles find that firms and industries tend to focus on different types of innovation depending on the maturity of the dominant design. The overall logic is as follows. When the dominant design is yet to emerge, smaller entrepreneurial firms set out to create products that fulfill an emerging need, resulting in an industry characterized by ill-defined innovation targets and fragmented and unstable markets with many diverse products (Abernathy and Utterback, 1978; Utterback, 1994). After enough experimenting with alternative product designs, a dominant design emerges, which encourages standardization. As a result, the industry stabilizes and consolidates into large-scale manufacturers producing standardized or slightly differentiated products, resulting in an overall slowdown in technological progress (Utterback, 1994). In these stabilized industries, firms dedicate their efforts to pursuing innovations that serve the firm's existing competence base, such as modular or incremental innovation (Abernathy and Clark, 1985; Henderson and Clark, 1990). However, as these firms tend to build their organization and innovation tasks based on recurrent tasks, they are not well equipped to accommodate innovations that disrupt these existing competences, such as architectural or radical innovations often produced by new entrants (Henderson and Clark, 1990). These observations on the dynamics of innovation are often used in the modularity literature to highlight one of its potential pitfalls. Similar to the stabilizing effect of the dominant design, pursuing a modular strategy requires the firm to create a robust product architecture and set of rules, which allow designers to work independently on modular level but still ensures that these modules can be mixed and matched to create product variants. This, however, may make it very difficult for the firm to produce or adapt to more radical or architectural innovations.

Fine (1998) adds another dimension to the theory of innovation dynamics. Based on observations in the computer industry, he introduces the double helix model, which holds that industry structures will shift from vertically integrated with integral product architectures to disintegrated supply chains with modular structures and back. The speed at which the industry follows this helix is dependent on industry clock speed (Fine, 1998). The contention that systems will migrate to and from modular forms has also been an important source for theory development in the modularity literature. Schilling (2000) uses it to introduce the 'modularity theory of the firm', where she introduces different forces, such as synergistic specificity and heterogeneity in input and demand, which will drive systems towards higher or lower levels of modularity. Chesbrough and Kusunoki (2001) use these observations to argue that, as technology shifts from integral to modular (or back), the optimal configuration of the firm also shifts.

3.3.3. MASS CUSTOMIZATION AND PRODUCT PLATFORMS

Identifying modularization as the best method for achieving mass customization, Pine (1993) prompted subsequent research on the role of modularity in achieving higher levels of customization without sacrificing important performance criteria. This has resulted in certain works within the mass customization literature, such as Pine (1993), Pine *et al*. (1993) and Kotha (1995), to be frequently cited in the modularity literature. Another extensively used source of inspiration are articles and books discussing product platforms. Product platform planning ensures that assets can be shared across a set of products (Robertson and Ulrich, 1998), and involves creating *"a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced" (*Meyer and Lehnerd, 1997, p. 39). Like product modularity, the use of product platforms revolves around designing products capable of accommodating a large set of current and future product variants, while still benefiting from having a standardized and common pool of components and subsystems (Wheelwright and Clark, 1992; Meyer and Lehnerd, 1997). As the use of product platforms and product modularity share several similarities, the two concepts are often used interchangeably in research. As a result, the drivers, benefits and characteristics of product platforms are often directly transferred to the modularity literature and vice versa.

Similar to product modularity research, the literature on product platforms first gained momentum during the 1990s, when the use of product platforms was ascribed the same benefits often connected with the use of product modularity. This typically includes economies of scale advantages, such as lower inventory and processing costs, and a reduction in the cost and time required to develop new products, while enabling the firm to provide increased product variety and respond quickly to different customer needs (Meyer and Lehnerd, 1997; Robertson and Ulrich, 1998; Muffatto, 1999). Likewise, the use of product platforms has also been advocated as a way for firms to achieve successful mass customization (Robertson and Ulrich, 1998). Compared to the modularity literature, however, the platform literature seems to be more aware of contextual factors that influence the extent to which the use of platform planning is appropriate. Hayes and Wheelwright (1992), for instance, highlight aspects such as industry maturity, rate of technology change, the rate at which competitors launch new products, the return on investment of platforms, customer support, and the firm's own resources, capabilities and strategies, to be important variables that might influence the appropriateness or timing of platform decisions (Hayes and Wheelwright, 1992). One particular case that has had a tremendous impact on both the product platform and product modularity literature is the so-called Sony Walkman case (Sanderson and Uzumeri, 1995). This case describes how Sony dominated the personal portable stereo market during the 1980s. This success is often attributed to Sony's ability to continuously provide a broad product line that was well adapted to very specific market segments, by basing its product development on a small number of platform projects, which provided the foundation for many derivative products (Sanderson and Uzumeri, 1995). Not surprisingly, the Sony Walkman case became one of the success stories and sales arguments in both the product modularity and product platform literature.

3.3.4. SUMMARY - ADJACENT RESEARCH

The findings of adjacent research have primarily been used to substantiate the positive effect of product modularity on performance. Pine's remark that "*The best method of achieving mass customization […] is by creating modular components that can be configured into a wide variety of end products and services*" (Pine, 1993, p. 196) has been widely used in the modularity literature to promote modularity as being key to mass customization (in e.g. Sanchez, 1999; Worren *et al*., 2002; Lau *et al*., 2007a; Howard and Squire, 2007; Lau *et al*., 2010). The findings of the product platform literature have also been used to promote modularity and to, amongst others, argue that modularity supports a black box approach to component design (Sanchez and Mahoney, 1996; Howard and Squire, 2007) and that modular architectures can be used as flexible platforms for leveraging a large number of product designs (Mikkola, 2003; Mikkola and Gassmann, 2003). The adjacent research studying the effects of component sharing and product complexity has been applied in a similar way. The study by Fisher *et al*. (1999), for instance, has been referred to in order to argue that component sharing (and thus modularity) reduces the cost of product development and production (Lau *et al*., 2007a; Mikkola and Gassmann, 2003; Mikkola, 2006; Lau *et al*., 2010). In addition, Nobeoka and Cusumano (1997) and Novak and Eppinger's (2001) observations of the auto industry have been used to suggest that product modularity allows the successful outsourcing of modules to suppliers (Lau *et al*., 2010), supports communication and coordination within and beyond firm boundaries (Jacobs *et al*., 2007) and enables firms to build subassemblies independently, which subsequently can be rapidly assembled to create different product configurations (Salvador *et al*. 2002; Jacobs *et al*., 2007). Modularity researchers have used the works commenting on the dynamics of innovation to argue for the interdependency between product, process and organizational design. Sanchez (1996; 1999), for instance, uses the work by Henderson and Clark (1990) to support his view, i.e. the mirroring hypothesis, that organizations organize development and production processes in a structure that reflects the architecture of the products they develop. Similarly, the article written by Von Hippel (1990) on task partitioning has been used to argue that a modular architecture has implications for the task partitioning and problem decomposition in product development processes (Ulrich, 1995; Mikkola, 2003). The works on innovation dynamics have provided the basis for theorizing about the move of systems towards higher or lower levels of modularity (Schilling, 2000; Chesbrough and Kusunoki, 2001) as well as commenting on the potential stabilizing effect pursuing modularity might have.

3.4. EXISTING AND FUTURE RESEARCH THEMES

The review of modularity and adjacent research points to some general research themes within the modularity field. This section elaborates on four of these themes.

The first research theme, primarily addressed by the research categorized as part of the exploration field, centers around defining and operationalizing modularity. Given that modularity theory has been inspired by a broad field of research areas – including systems, programming, design, product development, and innovation theory – it is no wonder that the terminology used to describe product modularity is broad and varied. However, the fact that there is a lack of a unified definition of modularity complicates the task of further theory development.

The second theme within modularity research examines how product modularity affects the organization of work. Based on observations made by authors who have commented on the dynamics of innovation (such as Abernathy and Clark, 1985; Von Hippel, 1990; Fine, 1998), authors within the modularity literature often assume a natural convergence between product modularity and process, organizational, and market modularity. This convergence or alignment is assumed to strengthen the positive effects of product modularity on performance. In particular, product modularity has been claimed to enable, or lead to the decoupling of, tasks in the manufacturing and product development processes within the firm itself as well as its supply chain.

The last two research themes highlighted in the following sections comment on and theorize about the performance effects of modularity as well as attempt to explain *how* product modularity influences performance. Given that the initial works on product modularity had the primary goal of promoting modularity, these works highlighted many of the potential benefits of adopting this design practice. Later literature, however, recognizes the need for a more elaborate exploration of the performance effects that result from adopting modularity. Therefore, a wide range of research – including modeling, case and survey research – has started to theorize about and, then, test the effects of modularity on performance. Even though empirical research has also begun to explain *how* product modularity influences performance, this research, however, is still very limited.

3.4.1. THEME 1: OPERATIONALIZATION OF MODULARITY

Even though research on product modularity has developed exponentially since the 1990s, the field is still characterized by conceptual ambiguity. While developing "*capacities to design and manufacture parts which can be combined in numerous ways"* (Starr, 1965, p. 132) and ensuring that a product consists of *"smaller subsystems that can be designed independently, yet function as a whole"* (Baldwin and Clark, 1997, p. 84) are intriguing thoughts, these authors and other researchers in the attention-seeking phase of modularity research did not seem to agree on what a modular product architecture actually constitutes. Recognizing the failure of the attention-seeking literature to arrive at a singular definition of modularity, the authors who are part of the exploration phase review this literature to derive more rigorous insight into definitions of modularity. However, after 20 years of modularity research, researchers still use an abundance of terms to treat and define modularity (see Table 3). There is no unified conceptual or operational definition of modularity – the term is still subject to debate. This inconsistency in defining modularity can partly be explained by the fact that the field has been inspired by different branches of theory with different terminologies. While aspects such as coupling, information hiding, interfaces, and functional binding might be well understood in their respective fields, the use of these abstract terms has complicated the task of creating a precise, understandable, coherent and, especially, unified definition of modularity.

Another issue in the modularity literature is that there are differences in the particular characteristics authors focus on when describing the concept. Sanchez and his colleagues, for instance, regard standard interfaces to be a key ingredient in modular design, and use this view on modularity to argue for their mirroring hypothesis (Sanchez, 1995; Sanchez and Mahoney, 1996). Another widely different (and rather unique) interpretation of modularity is from Ernst and Kamrad (2000), who use the degree to which the design is outsourced as a proxy of the degree of modularization in the respective product design. Even though outsourcing is often connected to modularization, several studies question whether this relationship actually exists (Ernst, 2005), making this particular interpretation of modularity questionable. Yet other examples of different ways in which the term modularity is understood can be found in Pil and Holweg (2004), who distinguish between different strategies to alleviate the negative impact of variety, including a) offering predetermined sets of options to customers, b) using and designing components to support multiple product configurations, and c) reducing the complexity of the final assembly line by assembling the complex modules in subassembly lines or at suppliers. Even though these authors only denote the latter of these three strategies to be "modularity", all three descriptions can be and are used in modularity theory.

Finally, irrespective of the way the concept is defined or the characteristics focused on, modularity is not an either/or property of a product system. Rather, product modularity is a matter of degree, and most product systems are somewhere on the continuum ranging from a non-modular to a modular product structure (Schilling. 2000; Campagnolo and Camuffo, 2010). So, the question is not whether a set of products is modular or not, but what degree of modularity a product system has, relative to comparable products. Furthermore, a product system can exhibit different levels of modularity, depending on the unit of analysis (Campagnolo and Camuffo, 2010). While not always explicitly articulated, most authors assess the degree of modularity by taking point of departure in the highest level of the product design hierarchy of the final manufacturer/assembler in the supply chain (Salvador, 2007).

Given the inconsistency in existing research when it comes to defining product modularity, some fundamental questions are, thus, still open for discussion. Not only should researchers strive towards a singular definition and operationalization of the concept, researchers also need to be more specific as to what type of products can and cannot exhibit modularity. For instance, the question arises whether product modularity is only useful for complex systems (as implicitly proposed by Baldwin and Clark, 1997) or whether it also can be used in more simple products. The ambiguity in defining modularity also makes it difficult for researchers and practitioners to understand how this concept relates to and differs from other concepts used in the literature. So, it is pertinent for researchers to question if and how modularity differs from other related concepts, such as platform thinking, component sharing, component commonality and standardization. It is especially useful for researchers to understand and convey the differences and similarities between platform thinking and product modularity. Even though these two concepts have been used interchangeably in existing research, the differences between them influence their usefulness and applicability in different settings (Magnusson and Pasche, 2014).

3.4.2. THEME 2: THE EFFECTS OF MODULARITY ON THE ORGANIZATION OF WORK

One widely studied proposition in the modularity literature is that the adoption of modularity enables or even results in a higher level of division of work within the firm itself, but also in the supply chain. From the very beginning of modularity research, authors have posited that modularity would facilitate specialized product development groups to focus on the development of components and coordinate their efforts through the standardized product interfaces and overall design rules (Ulrich and Tung, 1991; Ulrich, 1995; Sanchez, 1995). In addition, these authors predicted that this organizational structure could also be extended to the supplier network of the firm, in which the firm would undertake the development of fewer components in-house as more development activities could take place in an extended network of modular development organizations (Ulrich, 1995; Sanchez and Mahoney, 1996; Sanchez, 1996). This prediction appeared to hold true in certain industries. Based on anecdotal evidence from the PC, hard disk, microcomputer and stereo systems industries, researchers have observed that the adoption of product modularity results in vertical disintegration of supply chains, where innovative activities are coordinated via the market place (Langlois and Robertson, 1992; Baldwin and Clark, 1997; Chesbrough and Kusunoki, 2001). However, as Baldwin and Clark (1997) note, modularity has also been adopted in the car industry, where the innovative efforts are still mostly localized at the original equipment manufacturers (OEMs). This finding is substantiated by Genba *et al*. (2005) and Ro *et al*. (2007) who, in their studies of modularization in the car industry, find that carmakers are still focused on the outsourcing of simpler modules and that OEMs still maintain a great deal of the engineering control. Likewise, based on a study of the aircraft engine and chemical engineering industries, Brusoni and Prencipe (2001) find no evidence for the conclusion that modularity results in an arm's length relationship between module and architecture developers. So, while the relationship between the adoption of product modularity and the prevalence of modular markets holds true in certain industries, these effects are not observed in other industries.

Sosa *et al*. (2004) provide some insight into the reasons why modularity does not necessarily lead to greater levels of division of labor. Based on evidence from the development of an aircraft engine, they conclude that explicit architectural knowledge cannot prevent some interfaces between components to be unspecified. These interfaces can only be identified during the design process itself. As the likelihood for component misalignment is higher across organizational and system boundaries, indirect interactions within the firm itself might be necessary to ensure efficient product development. So, as argued by Eom (2008, p. 15) "*a simple causal relationship between system modularization and organizational division seems to insufficient to explain the boundaries of the firm*". More research is, thus, needed in order to understand the relationships between product modularity and the organization of work within and across firm boundaries. As Campagnolo and Camuffo (2010) suggest, this could include research into the activities that firms move out as a result of increasing product modularization and an exploration of factors and drivers that influence the relationships between product, organizational and market modularity.

3.4.3. THEME 3: THE PERFORMANCE EFFECTS OF MODULARITY

A prominent theme in the modularity literature is the question how modularity affects firm performance. This theme is consistently recurring through all the phases in the modularity literature. For the early articles in the attention-seeking and conceptual theory development phases, conveying the potential performance effects of modularity was an important part of spurring academic and practitioner interest in modularity. Most of this literature was based on anecdotal evidence from well-known industries, such as the consumer electronics or car industries, and emphasize the potential benefits of adopting a modular design philosophy. Early case studies also have a very positive outlook on the use of modularity. Based on an analysis of the development of stereo systems and microcomputers, Langlois and Robertson (1992) argue that modularity enables customers to access a large area of product space and fine-tune the product offerings, while the division of labor in the supply chain allows suppliers to innovate autonomously and, thus, conduct rapid trial-and-error learning. In addition, Garud and Kumaraswamy (1993) attribute the success of Sun Microsystem's open system strategy to the concept of economies of substitution, for which modularity is key.

As theory developed, authors became more nuanced in their view on the effects of modularity. Arnheiter and Harren (2006) cautioned against treating modularity as a panacea, and researchers began to recognize the importance of a full exploration of the trade-offs associated with implementing modularity (Ethiraj, 2007; Campagnolo and Camuffo, 2010). Based on modeling, Ethiraj and his colleagues argue that too much modularity can have adverse effects on firm performance and conclude that nearly modular structures present the best trade-off between innovation benefits and imitation deterrence (Ethiraj and Levinthal, 2004; Ethiraj *et al*., 2008). Furthermore, around the turn of the century, authors observed a noticeable lack of empirical evidence validating the performance effects of modularity (Gershenson *et al*., 2003). After the turn of the century, one type of research in particular, i.e. survey research, started to examine the effects of modularity on firm performance based on larger scale empirical evidence. Table 5 provides an overview of key variables and sample characteristics of this survey research. In general, this line of research tests the effects of product modularity or modularity based practices on three performance areas (in bold), i.e. a) financial, b) operational performance and/or c) innovation or new product development performance.

In general, the survey research agrees that the use of modularity leads to better financial and operational performance. More specifically, the survey research generally concludes that product modularity supports growth in sales and overall firm profitability, as well as enables the firm to meet its financial objectives and ensure customer satisfaction. Most authors claim that the effect of product modularity on financial performance is indirect, i.e. mediated by model variety (Worren *et al*., 2002), delivery and flexibility (Lau *et al*., 2007a), flexibility and customer service (Lau *et al*., 2007b) or supply chain responsiveness (Bush *et al*., 2010). Even though authors agree that modularity improves overall operational performance (Ahmad *et al*., 2010; Liao *et al*., 2010), the conclusions are less straightforward and even conflicting when it comes to the effects of modularity on more specific performance measures. Based on an exploration of 57 tier one suppliers to the U.S. automotive manufacturers, modularity is found to improve cost, quality, flexibility, time, support, and delivery performance (Jacobs *et al*., 2007; Droge *et al*., 2012). The results from an analysis of 251 firms in the electronics, plastics and toys industries in Hong Kong also indicate a positive relationship between modularity and flexibility, customer service, and product innovativeness (Lau *et al*., 2007a; Lau *et al*., 2007b; Lau *et al*., 2009; Lau *et al*., 2010). However, Lau *et al*. (2009) do not verify a significant relationship between modularity and price, quality and delivery performance as reported by Jacobs *et al*. (2007) and Droge *et al*. (2012).

Inspired by the mass customization literature, survey data has also been used to verify product modularity as an enabler of mass customization. The research, however, also concludes that in order for modularity to be a mass customization enabler, it requires customer closeness (Tu *et al*., 2004) or coordination at cross-functional, cross-plant and supply chain level (Zhang *et al*., 2014).

Table 5 - Overview of modularity research

Authors	Key variables	Size	Industries	Geography
Jacobs et al., 2007	Supplier INT, Design INT, Manufacturing INT, **Operational PERF***			
Jacobs et al., 2011	Process M, Manufacturing agility, **Growth PERF**	57	Automotive Suppliers	North U.S.
Droge et al., 2012	Process M, Supplier INT, Customer INT, **Delivery PERF, Support PERF**			
Ahmad et al., 2010	Design INT, **Mass customization, Operational PERF**			
Danese and Filippini, 2010	Design INT, Supplier INT, **New product development PERF**			
Danese and Filippini, 2013	Supplier INT, **New product development PERF, Product PERF**	150+	Mechanical Electronics Transportation	Europe U.S Asia
Salvador and Villena, 2013	Supplier INT, Product inno., Process inno., **Cost PERF, Technical PERF**			
Zhang et al., 2014	Organizational flatness, Coordination, **Mass customization**			
Lau et al., 2007a	**Operational PERF*, Product PERF**			
Lau et al., 2007b	Supplier INT, Internal INT, Customer INT, **Operational PERF***			
Lau et al., 2009	Internal INT, **Operational PERF***	251	Electronics Plastics Toys	Hong Kong
Lau et al., 2010	Supply chain INT, **Product PERF**			
Lau et al., 2011	Product inno., **New product development PERF**	115	Electronics	Hong Kong
Duray, 2004	Customer involvement, **Inventory, Planning, Channel management**	196	Multiple	U.S.
*Tu et al., 2004***	Customer closeness, **Mass customization**	303	Multiple	U.S.
Bush et al., 2010	Supply chain responsiveness, IT infrastructure flexibility, **Financial PERF**	102	Multiple	U.S.
Vickery et al., 2015	Platform product, Manufacturing flexibility, **Launch speed**	169	Multiple	U.S.
*Liao et al., 2010***	Absorptive capacity, Manufacturing INT, **Operational PERF**	330	N.S.	U.S.
*Thatte, 2013***	**Supply chain responsiveness**	297	Multiple	N.S.
Hao et al., 2015	Tacit coordination, **Radical innovation**	121	Multiple	Shanghai
Howard and Squire, 2007	Relation specific assets, Information sharing, **Supplier INT**	104	Multiple	U.K.
Worren et al., 2002	Market context, Organization, Strategic flexibility, **Financial PERF**	103	Home Appliance	U.K, U.S.
Parente et al, 2011	Supplier INT, Cultural distance, **New product introduction**	111	Auto Industry	Brazil

Measured in terms of more specific performance areas* * Modularity based manufacturing practices*

Following the general discussion in theory regarding how modularity can be expected to influence innovation, a lot of articles within the survey research also focus on this particular relation. The results indicate that modularity has a positive effect on the performance of new product development or introduction when moderated or mediated by internal and external integration (Danese and Filippini, 2010; Parente *et al*., 2011; Danese and Filippini, 2013). Vickery *et al*. (2015) also conclude that modularity has a positive effect on the frequency and timeliness of product launches, but that this effect is mediated by the use of product platforms and manufacturing flexibility. An examination of manufacturing firms in Shanghai indicates that modularity also supports radical innovation, but interestingly enough, this relationship is found to be negatively moderated by tacit coordination (Hao *et al*., 2015). Based on an exploration of electronics manufacturers in Hong Kong, Lau *et al*. (2011) find evidence of an inverted U-shaped relationship between modularity and product innovativeness. These results confirm what Ethiraj and Levinthal (2004) concluded through simulation modeling, i.e. that too little or too much modularity has adverse effects on performance.

Thus, the survey research supports the conclusion that modularity improves overall financial and operational performance and supports mass customization. As demonstrated in Table 5, however, some of these findings are based on very limited samples, in terms of industries targeted and geographical scope. Furthermore, there are still questions that remain unanswered. In particular, more research is needed to determine how modularity affects the innovation potential of the firm. Even though the survey research indicates that modularity has a positive effect on overall product development performance and that it does not necessarily hinder radical innovation from taking place, little is still known about the long-term effects of modularity on the innovativeness of the firm. Moreover, considering the conflicting results reported in the literature, further research is needed to verify how modularity affects specific performance areas, such as cost, quality, and delivery performance.

3.4.4. THEME 4: FACTORS AFFECTING THE RELATIONSHIP BETWEEN MODULARITY AND PERFORMANCE

The research is very limited when it comes to analyzing *how* modularity influences performance. Some researchers suggest that modularity increases agility, flexibility and responsiveness on manufacturing, firm or supply chain level, which in turn improves performance (Worren *et al*., 2002; Bush *et al*., 2010; Jacobs *et al*., 2011; Vickery *et al*., 2015). By far most research focuses on how integration influences the relationship between modularity and performance. However, as illustrated in Table 6, the authors do not seem to agree what specific role integration plays in this relationship.

Some researchers argue that the successful implementation and use of modularity requires a high level of cross-functional or inter-organizational integration, i.e. increased levels of integration lead to better modularization, which will be reflected in better performance (Lau *et al*., 2007b; Lau *et al*., 2010; Tu *et al*., 2004; Zhang *et al*., 2014). Other researchers turn this relationship around, that is, they argue that modularity supports integration in design and manufacturing and with suppliers, which in turn positively affects performance (Jacobs *et al.*, 2007; Ahmad *et al.*, 2010; Droge *et al.*, 2012; Danese and Filippini, 2013).

Table 6 - Survey research in modularity and integration

Relationship	Authors	Integration	Performance
M → INT → PERF; M → PERF	*Ahmad et al. 2010*	Inter-functional design coordination	Mass customization
INT ↓ (M → PERF)	*Danese and Filippini 2010*	Supplier involvement Inter-functional integration	NPD time
M → INT → PERF; M → PERF	*Danese and Filippini 2013*	Supplier involvement	NPD time and product performance
M → INT → PERF; M → PERF	*Droge et al. 2012*	Supplier integration Customer integration	Delivery and support
INT ↓ (M → PERF)	*Hao et al. 2015*	Tacit coordination with partners	Radical innovation
M → MED → INT	*Howard and Squire 2007*	Collaboration with suppliers	
M → INT → PERF; M → PERF	*Jacobs et al. 2007*	Supplier, design and manufacturing integration	Cost, Quality, Flexibility, time
INT → M → PERF; INT → PERF	*Lau et al. 2007b*	Supply chain co-development	Product performance, flexibility and service
INT ↕ M; INT → PERF; M → PERF	*Lau et al. 2009*	Internal integration	Competitive capabilities
INT → M → PERF; INT → PERF	*Lau et al. 2010*	Supply chain integration	Product performance
INT → PERF; M → PERF	*Liao et al. 2010*	Manufacturing system integration	Manufacturing performance
INT → PERF; M → PERF	*Parente et al. 2011*	Supplier integration	New product introduction
M ↓ (INT → PERF)	*Salvador and Villena 2013*	Supplier involvement	Cost and technical performance
INT → M → PERF; INT → PERF	*Tu et al. 2004*	Customer closeness	Mass customization
INT → M → PERF; INT → PERF	*Zhang et al. 2014*	Cross-functional, plant and supply chain coordination	Mass customization

Yet another group of researchers focus on the interaction or moderating effects of modularity and integration on performance (Lau *et al.*, 2009; Danese and Filippini, 2010; Salvador and Villena, 2013; Hao *et al.*, 2015) or do not directly focus on the relationship between integration and modularity, but look at both separately as key variables in influencing performance (Liao *et al.*, 2010; Parente *et al.*, 2011).

Thus, so far, survey research mostly is limited to one practice, i.e. integration, in explaining *how* modularity influences performance, and researchers cannot seem to agree on which specific role this practice actually plays. Other variables, however, are also important in exploring the effects of modularity on the manufacturing firm. Even though the survey research uses some traditional control variables in their analyzes, such as firm size, more effort could and should be put into analyzing in which types of firms, industries, and environments the findings hold true. Furthermore, the research could be supplemented by more descriptive statistics that, for instance, analyzes in what types of contexts the use of product modularity is prevalent.

3.4.5. SUMMARY - RESEARCH THEMES

Based on the considerations and critiques formulated in the previous sections, Table 7 provides an overview of the directions future modularity research could take. This list is not exhaustive, as other areas could also be pertinent for modularity researchers, areas that have not received as much attention in the literature so far. These could include the development of performance measures to analyze the effectiveness and efficiency of modularity (see e.g. Meyer *et al.*, 1997), an analysis of how the implementation of modularity changes incentive systems and employee relationships (Sanchez, 2000), how product architecture and process design decisions affect each other (Ernst and Kamrad, 2000), and how the use of different *types* of modularity influence firm performance, supply relationships and production design (Salvador *et al.*, 2002).

Furthermore, as this literature review has been confined to literature discussing the implications of product modularity on manufacturing firms, some other major research areas have been ignored. This includes one of the major themes in the design theory and engineering management literature, which focuses on how to *implement* modularity (Salvador *et al.*, 2002). Research within this area could, for instance focus on factors that might accelerate or hinder the development of modular product architectures (Campagnolo and Camuffo, 2010) and discuss what implications the use of different modularization methodologies has on the resulting product structure.

Table 7 - Potential future research directions

Research theme 1: Operationalization of modularity
Summary: The concept of modularity is still ill-defined as authors use similar, yet different definitions of modularity and focus on different modularity characteristics in their definitions, which, in turn has implications for the theory developed by these authors.
Potential areas for future research: How should modularity be defined and measured? Does the existing terminology give an adequate picture of what modularity is? Given that modularity is a "matter of degree", how can we determine the difference in the degree of modularity between different product systems? Can modularity be used to describe all product types, or does it only makes sense to use it for more complex products? What similarities and differences are there between product modularity and related concepts?
Research theme 2: Modularity and the organization of work
Summary: While authors have posited that there is a direct relationship between product, organizational and market modularity based on observations in the consumer electronics industries, other authors have used evidence from automotive industries to conclude that product modularity does not necessarily lead to organizational and market modularity.
Potential areas for future research: Is there a relationship between product, process, organizational, and market modularity and, if so, what factors and drivers influence this relationship? Why does this relationship exist in some industries, while other industries do not exhibit high levels of market modularity? What kinds of activities are traditionally outsourced in relation to the use of product modularity?
Research theme 3: Performance effects of modularity
Summary: Attention-seeking and conceptual theory propose that modularity has many potential benefits. While survey research verifies the overall positive effect of modularity on performance, it is not clear how modularity influences specific performance dimensions and the innovation potential of the firm. Furthermore, most modularity research is limited to one or a few industries and geographical areas.
Potential areas for future research: How can a firm determine its "optimal" level of modularity? What specific performance effects and trade-offs can firms expect when implementing modularity? How does modularity influence, for instance, cost, quality and delivery performance? How does modularity affect the innovation potential of firms? How does modularity affect the innovation and overall performance of the firm in the long run? Is there a positive or negative relationship between the implementation of modularity and the firm's ability to adjust to or support architectural and radical innovation? Do the findings reported in the literature hold outside industries and geographical areas considered so far?
Research theme 4: Factors affecting the relationship between modularity and performance
Summary: So far, only one practice – integration – has been in the center of attention when attempting to explain *how* modularity influences performance, and researchers do not even seem to agree on what role this practice plays.
Potential areas for future research: What is the role of integration in the modularity-performance relationship? Are internal and external integration prerequisites of successful modularization, or does modularity foster a higher degree of integration within and across firm boundaries? Does integration influence the strength and nature of the modularity-performance relationship? Can all firms expect the same effects when implementing modularity? If not, for what contextual factors such as type of product, type of firm and market and competitive environment, is the use of modularity appropriate and what factors influence the modularity-performance relationship? In what types of contexts is the use of modularity prevalent? What factors influence the choice of product architecture? What practices are often implemented in relation to modularity and what practices are complementary to modularity?

3.5. CHOICE OF RESEARCH DIRECTION

Already at the beginning of modularity research, Ulrich and Tung (1991) asked the question: How much modularity is optimal? So far, the literature has only come up with a partial solution. Researchers agree that too much and too little modularity has adverse effects on firm performance (Ethiraj and Levinthal, 2004; Lau *et al*., 2011) and that 'nearly modular systems' may present the best solution. But, what is 'just enough' modularity? What factors influence what degree of modularization is appropriate for a specific firm? Or, in other words, what can a specific firm expect when pursuing modularization?

To help answer these questions, this thesis has the overall purpose is to explore *how* product modularity influences the manufacturing firm and its performance. Despite the relevance of other research areas, this particular research direction is chosen particularly because practitioners need more than general, qualitative argumentation about the potential benefits and drawbacks of modularity, in order for them to be able to assess whether modularity is appropriate for their particular context. As other researchers also have remarked, there is a need for a more detailed exploration of the performance effects and trade-offs associated with modularity (Ethiraj, 2007; Campagnolo and Camuffo, 2010). Furthermore, there is a notable lack of research addressing the contingency factors influencing the use and applicability of modularity in different contexts (Magnusson and Pasche, 2014).

Throughout the development of modularity research, many authors have suggested that product modularity positively affects firm performance. Taking outset in the mirroring hypothesis, the use of modular processes and organization is often proclaimed to further the potential benefits of modularity. In particular, research proposes that using a modular design enables firms to adopt late point differentiation, concurrent manufacturing and modular product development. However, research has yet to determine whether this is true, and, even more important, whether these practices enhance the performance effects of modularity. In addition, other complementary practices can be identified within the product management, variety management and mass customization literature, where product modularity is often treated as one of the potential ways to solve the trade-off between high product variety and customization and other operational performance areas.

Even though many authors do seem to agree that product modularity may influence the way in which a firm structures its processes and functions, not many authors seem to look at or even notice the opposite proposition: that the firm and context themselves may influence the appropriateness of modularity. Although Ulrich (1995) noted that *"no single architecture is optimal in all cases"*, the majority of authors list the effects of modularity on the firm, without explicit reference to the question whether these effects are universal for all firms. Except for promoting modularity as a way for dealing with complex products, very little literature focuses on the type of products, firms and contexts for which product modularity is relevant. There is no such thing as an 'optimal level of modularity' for all types of firms and contexts – the appropriate level of modularity is likely to be dependent on numerous factors, some of which have already been discussed in the modularity literature.

Feitzinger and Lee (1997) for instance, highlight that the appropriateness of standardization (and thus modularity) depends on the uncertainty of product development across geographical markets, the lead time required to replenish stocks, the length of the product life cycle and the cost of shipping of finished products. Schilling (2000) adds to the list of factors by proposing that modularity is only appropriate in environments where there is both input and demand heterogeneity, and when the products exhibit a low level of synergistic specificity. In addition, researchers have found that the appropriateness of modularity may also depend on the customers' technological expectations, customer sophistication, customer demand for customization and other demand characteristics, the rate of innovation in component technologies, the speed at which technology and demand changes, and the costs associated with producing the modules and product (Chung *et al*., 2012; Kamrad *et al*., 2013; Magnusson and Pasche, 2014). However, even though researchers are aware of factors that might influence the appropriateness of modularity, more empirical evidence is needed to determine which of these factors influence the relationship between modularity and performance and, then, how.

So, even though existing survey research indicates that modularity can help firms to improve their overall operational and financial performance, as well as be a key ingredient in mass customization efforts, more contingency-based research is needed to help determine which types of performance effects individual firms can expect from modularization efforts. More empirical evidence is needed – from more industries and with a larger geographical scope – that addresses important internal and external contingencies and examines complementary practices that influence the nature and strength of the effects of modularity on firm performance. All in all modularity research could benefit from a more deliberate analysis of contextual factors and organizational practices that influence the modularity-performance relationship. This could help researchers determine all-important questions such as whether all firms in all geographical areas can expect (the same) benefits from modularity and what type of organizational characteristics and practices enhance the potential performance effects of modularity. This in turn would help practitioners understand which particular effects they could expect or aim for when implementing modularity.

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CHAPTER 4. PUTTING MODULARITY IN A BROADER CONTEXT

During the 1960's, Joan Woodward pioneered a new perspective to organizational studies. Based on a survey of manufacturing organizations in the U.K., Woodward observed that more successful firms adapted their organizational structure to the technical complexity of their production systems (Pugh and Hickson, 2000). In her own words: "*Different technologies imposed different kinds of demands, and these demands had to be met through an appropriate structure. Commercially successful firms seemed to be those in which function and form were complementary*" (Woodward, 1965, p. vi). This was the beginning of a new type of organizational theory, later denoted contingency theory, which builds upon the basic premise that 'there is no best way'. That is, there is not one specific type of organizational structure that makes all organizations perform highly (Donaldson, 2001). More specifically, contingency theory concludes that the effectiveness of organizations depends on the fit between a) design characteristics (the structural characteristics of the organization) and b) contingency factors (the characteristics of the context to this structure). The structural characteristics a firm exhibits depend on how the firm chooses to divide its labor as well as the mechanisms employed to coordinate work, and include structural features such as the degree of job specialization, standardization and formalization, unit size and grouping, the level of vertical and horizontal decentralization, and the use of planning and control systems in the firm (Mintzberg, 1979).

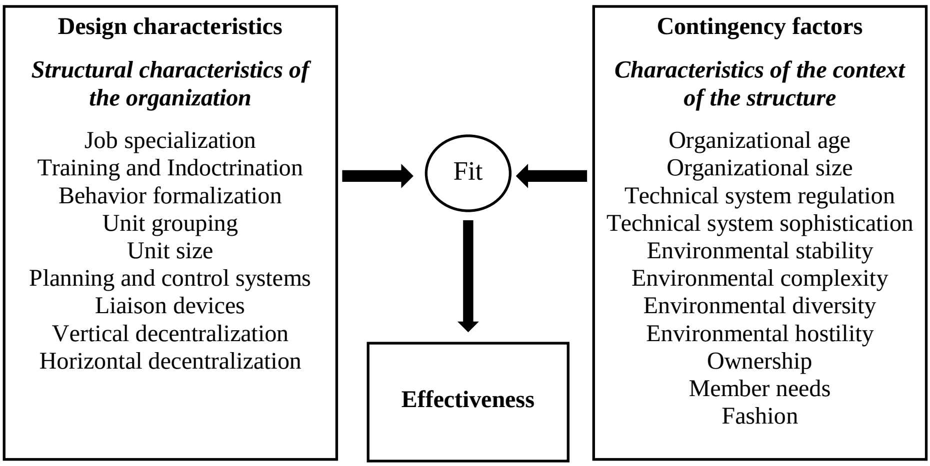

Figure 3 - Summary of contingency theory
(Mintzberg, 1979, p. 220)

Contingency factors to the organizational structure include characteristics of the firm's environment (Burns and Stalker, 1961; Lawrence and Lorsch, 1967), its size (Pugh *et al.*, 1963) and strategy (Chandler, 1962; Miles *et al.*, 1978; Porter, 1980), characteristics of the firm's technology and processes (Woodward, 1965; Perrow, 1967; Thompson, 1967), and the importance of and the degree to which the firm has control over resources (Pfeffer and Salancik, 1978). Based on an analysis of around 350 references, Mintzberg (1979) summarized many of the hypotheses in contingency research, visualized in Figure 3. Whereas contingency theory traditionally focuses on the fit between structural and contextual characteristics, that is, based on the proposition that the structure of an organization must fit its context in order for the organization to perform well (Drazin and Van de Ven, 1985), this thesis focuses on identifying important contingencies and practices that determine the appropriateness and effectiveness of product modularity in a given firm.

The overall purpose of this chapter is to propose and discuss different contingencies and practices that could influence the strength and nature of the relationship between product modularity and performance. This chapter, thus, provides theoretical background for the empirical work conducted in relation to the PhD thesis. However, before identifying contingencies and practices, there is a need to detail what modularity actually signifies. Therefore, this chapter will firstly propose a definition of modularity by delineating between design characteristics and product effects of modularity (section 4.1). Taking outset in these product effects, the next section will detail how theory proposes modularity to influence performance (section 4.2), before introducing contingencies and practices theory has suggested to influence the relationship between product modularity and performance (sections 4.3-4.6).

4.1. DEFINING MODULARITY

As discussed in the previous chapter, the definition and operationalization of product modularity varies from publication to publication. The definitions from the most cited researchers in the modularity field are listed in Table 8, together with an indication of what type of attributes the authors focus on in their definition.

This table clarifies the fact that there is no unequivocal way to measure and define modularity in existing literature. Overall, research fails to make a clear distinction between two different perspectives of modularity, that is, it does not make a distinction between 1) the attributes a modular product structure exhibits (*design characteristics*) and 2) the effects a modular product structure has on product level (*product effects*).

Table 8 - Definitions used in modularity research

Ulrich and Tung (1991) Functional binding Independency	*"We view modularity as depending on two characteristics in design: 1) similarity between the physical and functional architecture of the design, 2) Minimization of incidental interactions between components"*. (p.2)
Ulrich (1995) Functional binding Loose coupling	*"A modular architecture includes a one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies de-coupled interfaces between components."* (p. 422)
Sanchez (1995) Interface standardization	*A modular design results when standardized interfaces in a product architecture are specified to permit a range of variations in any given component without requiring changes in the overall product design or in the designs of other components in the product"* (p. 142)
Sanchez and Mah. (1996) Interface standardization Loose coupling	*"Modularity is a special form of design which intentionally creates a high degree of independence or 'loose coupling' between component designs by standardizing component interface specifications."* (p. 65)
Baldwin and Clark (1997) Information hiding Loose coupling	*"A modular system is composed of units (or modules) that are designed independently but still function as an integrated whole. Designers achieve modularity by partitioning information into visible design rules and hidden design parameters."* (p. 86)
Baldwin and Clark (2000) Information hiding Independency	*"Modularity is a particular design structure, in which parameters and tasks are interdependent within units (modules) and independent across them - this can be determined by preparing a design or task structure matrix."* (p. 88) *"Modular task structures can be created through a process of modularization - creating visible (design rules) and hidden design parameters."* (p. 89)
Schilling (2000) Product separability Loose coupling Component combinability	*"Modularity is a general systems concept: it is a continuum describing the degree to which a system's components can be separated and recombined, and it refers both to the tightness of coupling between components and the degree to which the "rules" of the system architecture enable (or prohibit) the mixing and matching of components."* (p. 312). *"Systems are said to have a high degree of modularity when their components can be disaggregated and recombined into new configurations - possibly substituting various new components into the configuration - with little loss of functionality"* (p. 316)
Langlois and Rob. (1992) Component combinability	*A modular system: "a group of sub products that consumers can arrange into various combinations according to their personal preferences."* (p. 297)
Garud and Kum. (1995) Interface standardization Product separability Component combinability	*"Production of components conforming to standard interface specifications also leads to modularity. Modularity allows components to be produced separately and used interchangeably in different configurations without compromising system integrity"* (p. 94)
Starr (1965) Component combinability	*"It is the essence of the modular concept to design, develop, and produce those parts which can be combined in the maximum number of ways."* (p. 138)

The delineation between design characteristics and product effects of modularity is shown in Figure 4. A modular architecture consists of two main design characteristics: standardized interfaces and standardized components. The first characteristic, standardized modules, refers to the design of modules that can be used in several product variants. To create standardized modules, a firm needs to ensure a relatively low degree of dependency between design parameters in the product, that is, create integrated components that are relatively independent from the components external to the module (Baldwin and Clark, 2000). Furthermore, the firms also must ensure that the module can perform the same function in several products by creating similarity between the overall physical and functional architecture of the design (Ulrich and Tung, 1991). The second design characteristic of modular architectures are standardized interfaces, which requires a firm to create specifications/design rules for the spatial interaction between modules as well as for how the modules exchange materials, energy, and information (Pimmler and Eppinger, 1994).

Product characteristics	
Standardized modules Modules are designed for the use in several products – enabled by functional binding and creating independency between modules	***Standardized interfaces*** The way the modules interact is standardized – enabled by creating design rules for how modules connect and interact

Product effects	
Component sharing Modules can be reused between variants and generations	***Component separability*** Modules can be built separately and are detachable
Loose coupling Modules can be designed independently	***Component combinability*** Modules can be mixed-and-matched to create variants

Figure 4 - Product characteristics and effects of modularity

In combination, standardized modules and standardized interfaces in a set of products result in certain effects of on product level (*product effects*), and enables the firm to:

- Use the same module in several product variants and product generations (*Component sharing*)
- Produce detachable modules separately (*Component separability*)
- Mix-and-match modules to create product variants (*Component combinability*)
- Design modules independently without the disrupting overall product design (*Loose coupling*)

In conclusion, modularity is a function of the degree to which a firm uses standardized modules and interfaces, which accommodates loose coupling and component sharing, component separability, and component combinability. The design of standardized modules and interfaces is enabled by principles such as mapping and binding functions to the product structure, decomposing the product to identify relatively independent component groups and using the information hiding principle, i.e. creating design rules that determine how modules interact[2]. Relating this to the terminology used in existing modularity literature outlined in Tables 3 (p. 14) and 8, I argue that information hiding, independency, life cycle modularity, standard components, and interface standardization are all ways in which modularity is achieved, whereas component sharing, component combinability, loose coupling, and product separability are effects or abilities that product modularity facilitates.

Given my suggestion that modularity is a function of the degree to which interfaces and modules are standardized in a set of given products, it is natural to question what actually constitutes the end-points of the scale from non-modular to highly-modular. Some authors argue that the opposite of modularity is integral architecture which "*includes a complex (not one-to-one) mapping from functional elements to physical components and/or coupled interfaces between components*" (Ulrich and Tung, 1991, p. 422). I propose a different, albeit complementary view, and argue that non-modular products are products that consist of subsystems, components, parts and interfaces that are only specific to that product. Firms with non-modular products, produce product variants that do not share the same or similar interfaces or modules. Given that most firms have some degree of component sharing between their products and also tend to adhere to some design rules for how these components are to interact, most firms produce or assemble products that are somewhere along the scale of non-modular to modular. Therefore, most firms considering to adopt modularity actually contemplate the question whether they should explicitly start to design products that exhibit higher levels of module and interface standardization.

This definition of modularity also helps distinguish the term from other related terms used both in modularity literature and adjacent research, such as platform thinking,

[2] Paper 1 and 2 represent earlier attempts to operationalize modularity, and propose similar, yet slightly different views on modularity. Paper 1 proposes a measure of modularity using two product characteristics, 1) the extent to which psychical connections between components are standardised and ensure that the product is decomposable, and 2) the extent to which the components are standardised and have a clear and distinctive function. Paper 2 proposes three design characteristics (standardized component interfaces, standardized components and dedicated functions) and five product effects (assemblability, carry-over, commonality, independence and combinability). Instead, the later revision presented in the thesis 1) identifies dedicated functions as a principle by which modularity can be achieved (and not a design characteristic), 2) uses the term standardization of interfaces, which encompasses more than the standardization of physical connections, 3) uses the term loose coupling instead of component independence, 4) uses the term component sharing to encompass both component carry-over and commonality, and 5) has less emphasis on assemblability and decomposability, as these might be, but not necessarily are, product effects of modularity.

component sharing and component commonality. In particular, this definition helps identify modularity as *one* of the ways to increase component sharing and component commonality, which means that many of the advantages and disadvantages connected to component sharing also are pertinent for firms employing modularity. It is however more difficult to distinguish between modularity and platform thinking, which also is one of the reasons for why these two concepts are used interchangeably in existing research. I have addressed the differences between these two concepts in Paper 3, a paper that contrasts platform thinking and product modularization based on a survey of Swedish product development practices. Platform thinking refers to the design, management and use of "*a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced*" (Meyer and Lehnerd, 1997, p. 39) and requires the firm to decouple the standardized platform components and interfaces from differentiating, variable platform elements (Baldwin and Woodard, 2009). Both product modularization and platform thinking aim to design (families of) products that can support a large range of current and future product variants, while still utilizing a common pool of components and subsystems. Both approaches also utilize economies of substitution, where technological progress is achieved by "*substituting only certain components of the multi-component system while retaining others*" (Garud and Kumaraswamy, 1993, p. 362). But, whereas product modularity focuses on the creation of interchangeable modules that can be mixed-and-matched according to customer demand (Schilling, 2000; Starr, 1965), platform thinking has an even stronger emphasis on standardization, and aims to create a standard base of subsystems and interfaces that are fixed over the life of the platform, where product variants are created by developing and adding distinctive variable components.

4.2. PERFORMANCE EFFECTS OF MODULARITY

Table 9 lists some of the benefits and costs authors typically associate with the implementation of product modularity in manufacturing firms. Whether the firm is capable to reap the benefits of product modularity depends on the firm's ability to define modules that can be effectively and efficiently used in their processes as well as fit well with customer needs. More specifically, it depends on whether the firm is able to define modules that can be developed, purchased, manufactured, and assembled efficiently and also can be combined into or be included in different product variants that suit customer requirements well. The design of these sets of modules, i.e. the design of modular systems that can be efficiently processed, is more difficult and requires a higher amount of initial development resources and time compared to the design of comparable interconnected systems (Baldwin and Clark, 1997). It also requires the firm to adhere to design rules and system architecture for prolonged periods of time. Given that these rules and architecture often become embedded in the organization of the firm's product delivery system, modularity may result in the firm becoming less responsive to architectural or radical innovation (Ulrich and Tung, 1991).

Table 9 - The proposed benefits and costs of modularity

Lower product costs and increased reliability
Component standardization can provide economies of scale benefits in manufacturing and purchasing; it allows for higher volume, more efficient production and the relatively low cost purchase of standard components (Ulrich and Tung, 1991; Erixon, 1996). Moreover, the reuse of components supports learning curve effects - the quality and speed of manufacturing processes can be improved incrementally, and leads to reduced complexity costs in inventory management (Ulrich, 1995; Sanchez, 1999). A high degree of component commonality can, however, also jeopardize product differentiation (Pasche and Sköld, 2012)
Low cost, rapid product development
Modularity enables the firm to continuously accommodate necessary changes on component basis, without disrupting the design of the entire product (Ulrich and Tung, 1991; Erixon, 1996). This increases the frequency and speed of new product introduction and lowers development costs (Ulrich, 1995; Erixon, 1996; Sanchez, 1996), enables economies of substitution, supporting the reuse of knowledge and components between product designs, (Garud and Kumaraswamy, 1995) and enables real-time market research (Sanchez, 1999). It also supports black box sourcing, where the supplier not only produces the component, but designs and develops it according to interface and functional specifications (Sanchez and Mahoney, 1996)
Mass customization and strategic flexibility
Modularity enables firms to mix and match components to increase product variety at no sacrifice of volume or cost (Starr, 1965; Sanchez, 1996; Sanchez, 1999). Modularity increases the firm's product flexibilities (including mix, change-over and modification flexibility) (Sanchez, 1995) and responsiveness to changing markets and technologies (Sanchez and Mahoney, 1996)
Late point differentiation
Dividing the product into standardized and variable components can support late point differentiation, where standard components can be manufactured-to-inventory and combined with variable components on the basis of customer orders (Ulrich and Tung, 1991; Ulrich, 1995; Sanchez, 1995; Sanchez, 1999)
Product testing and service
Having standardized interfaces enables black box component testing, and facilitates after-sales service, maintenance and product use (upgrades, add-ons, wear, consumption) (Ulrich and Tung, 1991)
Product performance
The lack of function sharing in the product might result in an increase in product mass and size, which in turn might increase variable product costs and excess capability (Ulrich and Tung, 1991; Ulrich, 1995). Turning a parameter into a rule may result in the designer not discovering superior designs (Baldwin and Clark, 2000)
Modular versus architectural innovation
The decomposition of the product architecture in modules results a heightened rate of component innovation (Sanchez and Mahoney, 1996) However, it might also create organizational barriers to accommodate architectural innovation and increase risk of product design imitation (Ulrich and Tung, 1991). Modular systems are more difficult to design compared to interconnected systems (Baldwin and Clark, 1997) and requires the firm to periodically revise or create new product architectures (Sanchez and Mahoney, 1996).

Blindly standardizing the modules and interfaces in a given product portfolio may also result in the designers not discovering or pursuing superior designs (Baldwin and Clark, 2000), and lock a system into an architecture that is bound to become suboptimal (Eom, 2008). As noted by Langlois (2002), one question is whether firms adopting modularity can become stuck in inferior performance trajectories because of the relative costs associated with re-modularization (Langlois, 2002). The fact that modularity requires the design of generic modules for multiple applications, might result in excess product size and mass (Ulrich and Tung, 1991) and may not optimize system performance as the product might achieve greater functionality by its components being specific to one another (Arnheiter and Harren, 2006; Schilling, 2000). In the discussion of the role of modularity in achieving mass customization, Morris and Donnelly (2006) also note that the larger the standardized modules are, the more specific their application tend to be, and the more difficult it is to customize the end-products. Even though the simplicity and transparency of modular systems allows the firm to efficiently develop and produce modules, it also makes it easier for competitors and supplier to imitate the entire product design, and, thus, modularity might undermine the firm’s position in the marketplace in the long run (Pil and Cohen, 2006; Baldwin and Clark, 1997).

Given these potential costs and risks related to designing and using modular product portfolios, the question remains why modularity has become increasingly popular in organizations. The obvious answer is that modularity not only creates costs and risk, but also has benefits. The benefits of adopting modularity can be directly related to the effects the implementation of modularity has on product level - see Figure 4.

Component sharing - The reuse of modules across product variants and generations supports both economies of scale and learning curve advantages. Modularity enables firms to manufacture larger batches of standard components and modules, which reduces manufacturing costs and time by, amongst others, decreasing overall change-over and set-up times and inventory levels, increasing man, machine, and material efficiency, and enabling low-cost purchase of standard components (Ulrich and Tung, 1991; Erixon, 1996). Moreover, ensuring that components, modules and interfaces remain fixed over prolonged periods of time supports the incremental improvement of the manufacturing system, which, in the long run, can lead to significant performance improvements in terms of costs, speed and quality (Erixon, 1996; Sanchez, 1999). However, if not managed correctly, the possible overuse of standardized module across product lines can results in excess product similarity (Ulrich and Tung, 1991; Arnheiter and Harren, 2006).

Loose coupling - Modularity, and specifically the simplification and standardization of interfaces, allows for design and development activities to take place on module basis without having to disrupt the overall product design. Modularity is key in helping firms achieve economies of substitution, where the “*costs of designing a higher performance system, through the partial retention of existing components, is lower than the cost of designing the system afresh*” (Garud and Kumaraswamy, 1993, p. 362). Modularity and module-based development enables firms to develop or improve products more quickly at a lower cost, as product development and improvement involves substituting components, not entire products (Sanchez, 1999).

It enables the firm to focus their development activities on those components that are subject to higher rates of technological change and improve the predictability and timing of product development outcomes (Sanchez, 1999). Moreover, in some industries, modularity has enabled firms to adopt black box sourcing and autonomous innovation (Langlois and Robertson, 1992), where different firms or suppliers can take on the responsibility for developing different parts or modules of the product (Baldwin and Clark, 1997).

Component combinability - One of the primary reasons for the adoption of modularity is that it enables firms to combine different sets of modules to create a relative large variety of end-products at no sacrifice in volume or costs (Starr, 1965; Sanchez, 1999). Thus, modularity represents one of the ways for firms to overcome the variety-operational performance trade-off (Salvador *et al.*, 2002), as product variety can be achieved without flexible component production equipment (Ulrich, 1995) and demand uncertainty is accommodated for more easily (Sanchez, 1999).

Component separability - The fact that modularity enables firms to build modules separate from the main assembly line enables the firm to adopt concurrent manufacturing and conduct testing on module level, which in turn helps reduce manufacturing lead time and improves overall product quality (Ulrich and Tung, 1991; Feitzinger and Lee, 1997; Arnheiter and Harren, 2006). Furthermore, dividing the products into sets of standardized and customized components enables the postponement of differentiating elements (Feitzinger and Lee, 1997), where standard components can be manufactured-to-stock and combined with variable components on the basis of customer orders, that is, assembled-to-order (Ulrich and Tung, 1991; Ulrich, 1995; Sanchez, 1995; Sanchez, 1999). Last but not least, having standardized interfaces that ensure that modules are detachable from the final product configuration facilitates after-sales service, maintenance and product use (upgrades, add-ons, wear, consumption) (Ulrich and Tung, 1991; Ulrich, 1995). On the other hand, this also means that modularity can lead to an increase in costs and time, as it can result in customers having to replace an entire module when only one sub-component of this module is faulty (Arnheiter and Harren, 2006)

The above summary of the proposed performance effects of modularity is filled with speculation - modularity "may result in" or "can lead to". Little is known about in what contexts and settings such speculations hold true and how environmental and firm-specific characteristics influence the performance trade-offs associated with the implementation of modularity. Furthermore, although theory proposes certain practices, such as postponement, concurrent manufacturing and autonomous design, to create or enhance positive effects of modularity on performance, little research has been conducted to verify these propositions. The remainder of this chapter outlines contingencies and practices that influence the modularity-performance relationship. It delineates between contextual and organizational characteristics that might influence the appropriateness of modularity, and introduces manufacturing as well as product development characteristics and (integrative) practices that might influence how modularity influences firm performance.

4.3. CONTEXTUAL CHARACTERISTICS

During the 1990s, several authors observed a change in the context in which firms compete, that is, they observed that competition and markets were becoming more competitive and dynamic than ever before - products and technologies were starting to be developed at an accelerated pace, customers had become more varied and sophisticated in their taste, and the number and aggressiveness of competitors had increased (Hayes and Wheelwright, 1992; Sanchez, 1996; Pine, 1993). Based on these observations, practices such as mass customization, platform thinking and modularity were promoted as potential ways in which firms could compete in the changed competitive environment. Case studies verify that firms, such as Sony Walkman and Hewlett Packard, used these principles to achieve success in their respective marketplaces - enabling these firms to provide product variety and model longevity, without having to sacrifice other crucial performance parameters, such as quality, speed, or costs (Sanderson and Uzumeri, 1995; Feizinger and Lee, 1997). However, as noted by Magnusson and Pasche (2014, p. 15), "*[w]ithin the literature taking an engineering focused perspective on modularization and product platform development, the market demand for variety is often regarded as given*". In other words, it is naïve to assume that all firms are exposed to similar environmental characteristics and requirements or that modularity is appropriate for all type of markets.

In developing 'modular system theory', Schilling (2000) proposes that the more heterogeneous the inputs to, and the demands placed upon, a system, the more valuable re-combinability and, thus, modularity becomes. As modularity simplifies the product design and increases the ease of reverse engineering, modularity might actually only be fruitful in markets where there is large product heterogeneity and where customer preferences and technologies are complex, so that competing firms are able to modularize their products in unique ways (Pil and Cohen, 2006). So, theory proposes demand, input and product heterogeneity to be drivers behind the use of product modularity. However, as Magnusson and Pasche (2014) emphasize, modularity might obstruct a firm in creating truly individualized solutions for its customers, indicating that modularity might not be appropriate in highly heterogeneous marketplaces that have *very* high demands for customization and personalization.

In general, modularity theory often presumes that all firms experience dynamics, demand and supply uncertainty, and rapid technology development, and that modularity therefore is required to provide the flexibility and variety to enable firms to cope with these environmental characteristics (Eom, 2008). Kamrad *et al.* (2013) and Chung *et al.* (2012), for instance, argue that modularity is most valuable when customers are technically sophisticated and/or expect a series of future technological developments. Even though modularity is assumed to be positively associated with accommodating technological turbulence, and is even identified as being able to increase the pace of technological development in specific industries (Baldwin and Clark, 1997), the question on the magnitude and types of technological changes a modular architecture can and cannot accommodate is still open. I propose that the adoption of modularity might not be appropriate in *highly* immature or turbulent industries, since the initial design efforts required to create a modular product portfolio are much higher than creating comparable integrated systems (Baldwin and Clark, 1997). The extra costs and time spent during the system-level design of a modular product portfolio need to be compensated for later in the product life cycle. This includes, for instance, the firm reaping the benefits from subsequent modular innovation, economies of scale and learning curve effects. Therefore, only once the dominant design and architecture of the product has been created and tested and is not to change for longer period of time, successful standardization of the components and interfaces can follow (Utterback, 1994) and the long-term benefits of this standardization can be achieved. This also means that the implementation of modularity locks the firm into specific technological and architectural trajectories for substantial periods of time (Pil and Cohen, 2006). When the industry is immature or turbulent and, consequently, the degree and rate to which the underlying technology in the product changes are high, firms may therefore not be able to reap the long-term benefits of modularization before yet another design or architecture emerges. Kamrad *et al*. (2013) add to the story by concluding that the value of modularity diminishes with the overall rate of change in component technologies, that is, they conclude that when there is an overall high rate of technological change in *all* the underlying components of a product, an integral product upgrade strategy might be more useful for firms. However, they also find that modularization is beneficial when there are *differential* rates in the improvement of components (Kamrad *et al*., 2013). This is consistent with the “economies of substitution” logic proposed by Garud and Kumaraswamy (1993). That is, modularization is advantageous for a firm if it is able to reuse standard modules between several product generations, while localizing their development activities to those modules that exhibit higher rates of technological change. So, modularization is only appropriate in environments where the rate of technological change can be localized to a subset of components, and thus, not appropriate in very turbulent and immature environments exhibiting high rates of change in all the underlying component technologies.

Thus, contextual factors such as the a) heterogeneity and complexity of products, technology, and customers, b) degree to which the customers demand customization and c) dynamics of supply, customer demand, and technological development affect whether and the extent to which modularization is beneficial. The overall suggestion in existing theory is that modularity becomes more valuable when demands, inputs and existing products are heterogeneous, where customers are technologically sophisticated and expect a series of future technological development, and where this development is accommodated by differential rates of improvement in the underlying pool of components. However, in very stable (with highly predictable technological development) or very immature industries (with high rates of technological change in all underlying components) modularity is less appropriate.

4.4. ORGANIZATIONAL CHARACTERISTICS

Prevalent firm-specific contingency variables in traditional contingency theory are firm strategy, size and age. These variables do not, however, dominate the modularity literature, even though they might have some say on whether modularity is appropriate for a given firm. The size of the firm can influence the appropriateness and effects of modularity by influencing whether the firm has enough resources to pursue modularization, and enough volume to reap the benefits of increased standardization. Related to organizational age are firm experience and maturity, which may also influence the appropriateness and effects of modularity. As noted by Pil and Cohen (2006), a firm's experience with using modular principles is likely to strengthen the positive effect of modularity on performance. Furthermore, as mentioned in the previous section, it is probable that highly immature firms, which have not yet developed or adhere to a dominant product design, first need to stabilize their product architecture before being able to design an effective and efficient modular system. The strategy of the firm might not be compatible with the pursuit of modularization, either. Related to the prior section on environmental characteristics that are likely to influence the appropriateness of modularity, I propose that firms pursuing cost leadership in stable, homogenous environments will not require the flexibilities that modularization can provide them. For these firms, there is little need for continuously developing modular components that can be mixed-and-matched and pure standardization might be a better approach for minimizing internal processing and development costs. Furthermore, the use of standardized product modules complicates the pursuit of pure customization, and modularity is therefore not appropriate for firms seeking to provide each and every customer with their own personalized solutions, So, I propose that modularity makes more sense for firms that seek to combine low-cost production *and* increased product and manufacturing flexibilities, that is, firms that seek to reap the cost, speed and quality benefits associated with component standardization combined with the increased product and manufacturing flexibility that stem from interface standardization. Another contingency that might influence the appropriateness of modularity is the characteristics of the firm's products. For instance, product modularity may not be feasible in highly complex products with very interdependent parts, where creating standard interfaces and standard components is virtually impossible. On the other hand, implementing product modularity is a way of simplifying complex product structures (Baldwin and Clark, 1997), and may be an unnecessary exercise in simple products with no differential components.

4.5. MANUFACTURING CHARACTERISTICS AND PRACTICES

All in all, however, most theorists who argue for modularity and its ability to overcome the variety-performance trade-offs implicitly assume that it is implemented in firms employing small or large batch manufacturing. In such a setting, modularity allows the firm to divide between a) the cost-efficient manufacturing and sub-assembly of standardized modular components and b) the final assembly process, which mixes-and-matches these components once customer requirements are known (Ulrich and Eppinger, 2012). In other words, modularity allows the firm to postpone or delay the point of product differentiation (Ulrich, 1995; Sanchez, 1995), and therefore facilitates the adoption of ‘modular’ manufacturing processes, i.e. standardization of early stages of the production process and postponement of differentiation and customization (Tu *et al*., 2004). Combining product modularity and postponement, through e.g. a midstream customer order decoupling point (assembly-to-order), is seen as key for firms pursuing a mass customization strategy (Feitzinger and Lee, 1997, Ahmad *et al*., 2010)

Another key enabler of mass customization is the adoption of flexible or agile manufacturing (Da Silveira, 2001). Modularity combined with flexible manufacturing can be a key asset in a mass customization program, as “*modular design and flexible manufacturing enabled Sony to produce a wide variety of models with high quality and low costs*” (Sanderson and Uzumeri, 1995, p. 780). In addition to building all their models around key modules and platforms, Sony adopted flexible manufacturing by employing small-lot production and multi-purpose machinery (Sanderson and Uzumeri, 1995). Thus, the use of flexible manufacturing systems and general purpose equipment might further enhance the positive influence of modularity on performance. Jacobs *et al*. (2011) find a positive relationship between product modularity and the adoption of flexible manufacturing systems, general purpose equipment, group technology and cellular manufacturing. Whereas the former two practices might *enhance* the performance effects of modularity, product modularity is said to enable the adoption of the latter two practices. Thus, while flexible manufacturing systems and general purpose equipment could play an important role as moderators of the modularity-performance relationship, group technology and cellular manufacturing are potentially mediators in the modularity-performance relationship. As mentioned by, amongst others, Ulrich and Tung (1991), Erixon (1996), and Ahmad *et al*. (2010), the adoption of modularity allows the parallel production of multiple modules, where manufacturer can use dedicated cells of machinery and teams to manufacture the independent modules.

4.6. PRODUCT DEVELOPMENT ORGANIZATION AND INTEGRATIVE PRACTICES

An important motive for using modularity is its ability to accommodate concurrent and autonomous development of modules by independent design teams (Sanchez, 1995; Sanchez and Mahoney, 1996). This mirroring hypothesis, which assumes that the product structure will reflect itself in the organization of development tasks, is not only restricted to activities within the firm, but also is one of the key arguments for authors who link the use of product modularity to increased outsourcing (Langlois and Robertson, 1992; Baldwin and Clark, 1997; Chesbrough and Kusunoki, 2001). Langlois and Robertson (1992), for instance, argue that modularity ultimately leads to vertical disintegration of the supply chain, where firms will heavily rely on an external network of suppliers in order to attain the best results of innovation efforts. Similarly, Garud and Kumaraswamy (1995) suggest that in order to firms to reap the benefits of economies of substitution, firms should “*emphasize the similarity between the design of technological systems and organizational* *systems*" (p. 94). More specifically, these authors argue that firms should combine the use of modularly upgradable systems with a network mode of governance.

The mirroring hypothesis builds on the premise that the standardization of the module interfaces will facilitate information hiding, which shields individual design teams or firms from having to possess detailed knowledge about any other components than the one they are responsible for (Bush *et al*., 2010). As a consequence, information sharing can be restricted to the information that is pertinent to the interface or module itself (Droge *et al*., 2012). Standardizing the interfaces as well as creating an explicit product architecture creates an "embedded coordination mechanism" (Sanchez and Mahoney, 1996) and a common language (Jacobs *et al*., 2007), which reduces inter-functional and cross-boundary communication barriers (Droge *et al*., 2012). The literature also suggests that the design of highly configurable products encourages a closer relationship with customers and thus facilitates a better understanding of customer needs (Droge *et al*., 2012). Thus, by restricting information sharing to key design parameters, modularity allows for more efficient coordination during the design process, both amongst the design teams themselves, but also between the design function and other internal functions as well as external partners.

Some authors, however, also note that although modularity may support loose coordination of the development work, it also requires iterative co-development with suppliers and customers in order to redefine interface specifications, maintain the compatibility of modules, reduce costs, and improve the performance of future products (Lau *et al*., 2009; 2010). Therefore, modularity might not provide enough cross-boundary coordination in itself. Instead, indirect interactions can provide an important coordination mechanism to ensure the alignment of module interfaces (Sosa *et al*., 2004). Mechanisms that facilitate increasing the level of cross-functional cooperation, communication and process overlap can be identified within the realms of product design, technological systems and organizational design (Paashuis and Boer, 1997).

Product design mechanisms: As mentioned, modularization can play an essential role in supporting cross-functional coordination, as it helps simplify cross-functional and cross-team information sharing and helps identify what tasks can be conducted in parallel by independent teams contra the tasks that need to be conducted in unison. However, other design and development practices can also support modularization efforts and increase the level of cross-functional integration. The most obvious practice often associated with modularity is platform thinking, where modularity is viewed as an important mechanism for facilitating successful development of product platforms (Vickery *et al*., 2015). Modularization efforts help determine which standardized components and modules should form the basis for future product family variants, and also creates the standardized interfaces that can help decoupling these standardized, common platform components and modules from the variable, peripheral components (Baldwin and Woodard, 2009). Both platform thinking and product modularity support the integration between the design function and other functions by enabling standardization, that is, the use of standard procedures, materials, parts, and/or processes for designing and manufacturing a product (Droge *et al.*, 2012). Other practices that have been linked to effective modularization efforts are quality function deployment (QFD), design for manufacturing (DFM) and design for assembly (DFA). These practices all fall under the “concurrent engineering” umbrella, as they aim to support the integrated, concurrent design of products and processes by having designers consider aspects from the entire product life cycle in their design efforts (Trygg, 1993). Where QFD supports customer integration by facilitating the translation of customer requirements into technical requirements for product development and design (Chan and Wu, 2002), DFM and DFA techniques support integration between manufacturing and design based on a set of guidelines that help taking manufacturing and assembly considerations into account as early as possible during product design (Boothroyd, 1994). QFD, DFM and DFA, thus, represent techniques that enable the firm to include customer, manufacturing and design considerations in their modularization efforts. One specific modularization method developed by Erixon (1996), denoted modular function deployment, suggests firms to start their modularization efforts off with QFD in order to translate customer needs and competitive priorities into current and future design requirements and end the effort with DFM and DFA in order to improve the ease of manufacturing and assembly of the product and its constituent modules. Other practices that are often not linked with modularity, but are associated with concurrent engineering include analytical methods such as failure mode and effect analysis (FMEA) and technological readiness level classification (TRL) (Trygg, 1993).

Technological mechanisms: In addition to these analytical methods, computer integrated manufacturing techniques have been essential in supporting concurrent engineering (Trygg, 1993). The integration of, for instance, computer aided design (CAD), computer aided engineering (CAE), and computer aided manufacturing (CAM) supports the automated coordination of design, engineering and manufacturing activities. Other technological mechanisms that can increase the degree of integration across departments and firm boundaries include IT systems that support the sharing of information on, for instance, order delivery status, sales and demand forecasts.

Organizational mechanisms: Organizational coordination mechanisms include arrangements firms use to coordinate labor, and can vary from temporary to permanent, informal to formal and cultural to structural arrangements (Paashuis and Boer, 1997). Informal mechanisms by which labor is coordinated include direct face-to-face communication, ad-hoc meetings and informal discussions. However, as we move from simple to complex tasks within an organizational setting, the amount of expertise needed to complete the task increases, and firms cannot rely merely on these informal mechanisms in order for tasks to be coordinated between the many participants (Mintzberg, 1979; Baldwin and Clark, 2000). Instead, the firm has to implement structural mechanisms or employ standardization in order to coordinate work (Mintzberg, 1979). One of the most prominent structural organizational mechanism by which development activities are coordinated across functional units in the organization is the use of cross-functional teams. Other structural organizational arrangements to increase the level of integration within a firm include job rotation, integrating managers, planning and control systems, project and matrix structures, and co-location (Mintzberg, 1979; Paashuis and Boer, 1997). All these arrangements are implementations of coordination mechanisms, in particular standardization of process, outputs or skills, and mutual adjustment (Mintzberg, 1979). Standardization includes the development of and adherence to rules, procedures and goals which, within a product development process, can be accommodated by the use of, for instance, stage-gate processes or performance management. Mutual adjustment relies on direct communication between, for instance, members of a project team, and can be accommodate for more agile types of project management (e.g. Scrum). Relating the above to the implementation and use of product modularity, the successful system-level design of a modular product system requires the firm to implement structural organizational mechanisms by which to ensure the collaboration and communication of participants from different functional areas within the organization - including design, manufacturing and marketing (Ahmad *et al*., 2010; Danese and Filippini, 2010). Detailed design activities, however, are less dependent on the organizational structure to coordinate labor. Instead, independent design teams can rely on component performance targets and interface specifications in order to coordinate the detailed design activities (Ulrich, 1995).

4.7. CONCLUSION

From the above review of existing definitions of modularity and items used to measure modularity, it is clear that, so far, literature often fails to make a clear distinction between the characteristics of a modular architecture, and the effects using a modular product architecture has on the resulting product portfolio. In this thesis, I argue that product modularity is a function of two design characteristics: the degree to which a firm has created 1) standardized interfaces (standardizing the way modules interact) and 2) standardized modules (modules designed for the use in multiple products) in a set of products. In turn, the use of standardized interfaces and modules enables firms to 1) share modules between product variants and generations (component sharing), 2) produce detachable modules separately (component separability), 3) mix-and-match modules to create product variants (component combinability) and 4) design modules independently (loose coupling). Each of these four product effects can be linked to the theoretically proposed benefits of using product modularity:

- Component sharing supports advantages associated with learning curve effects and economies of scale.
- Loose coupling enables economies of substitution and black box sourcing, and supports frequent, quick, and predictable new product development.
- Component combinability enables firms to overcome the variety-operational performance tradeoff.
- Component separability supports concurrent manufacturing and postponement as well as facilitates after-sales service, maintenance and product use.

However, there are also some disadvantages to the implementation of modularity. In particular, the initial system-level design and development of modular systems is more difficult and resource demanding compared to the design and development of functionally comparable integral systems. Furthermore, the use of modularity locks the firm to (potentially inferior) designs for prolonged periods of time and increases the potential for competitor imitation.

Whether a firm is capable of reaping the benefits of modularization effort depends to a large extent on its context. Theory proposes two environmental characteristics to be key in determining the appropriateness of modularity: environmental dynamics and heterogeneity. More specifically, existing literature suggests that modularity is most appropriate in dynamic environments where customers expect a series of future technological developments, but only when this technological change can be localized to a subset of components. Furthermore, it also reasons that the practices provide most value for firms that have complex products, heterogeneous inputs, and customers with heterogeneous and sophisticated product requirements who do not require truly individualized solutions. Therefore, modularity is neither appropriate for firms that seek to pursue cost leadership in very homogenous and stable markets nor appropriate for firms that seek to create only truly individualized solutions. Rather, modularity is more fitting for firms that need the speed, cost and quality advantages of mass producing standardized components, as well as the flexibility of quickly configuring and assembling the final product according to customer demand. Most theorists who argue for modularity's ability to overcome the variety-performance trade-off implicitly assume that it is implemented in firms manufacturing discrete physical products (Ulrich and Tung, 1991) within e.g. the automotive industry (Jacobs *et al.*, 2007; 2011) or the consumer electronics industry (Baldwin and Clark, 1997; Sanderson and Uzumeri, 1990; Kamrad *et al.*, 2013). In these firms, modularity enables the firm to postpone the final assembly activities until customer orders are received. Furthermore, the forecast-driven part of the production process can be conducted deploying group technology or cellular manufacturing principles, where the manufacturer can use dedicated teams and cells of machinery to manufacture and subassemble the standardized modules. It is the combination of being able to mass manufacture components with the ability to quickly provide customers with a variety of products that originally led Pine (1993) to propose modularity to be the best method to achieve mass customization. Another way in which firms can pursue mass customization is through the use of flexible manufacturing systems and general purpose machinery, two manufacturing practices that might enhance the performance effects of modularity.

In addition to affecting how the manufacturing process can be managed and organized, the implementation of product modularity also has a large impact on how product development work can be organized. By standardizing interfaces and creating explicit design rules, modularity is said to enable concurrent and autonomous product development of modules. As information sharing can be restructured to focus on key product information embedded in these interfaces and rules, product modularity additionally support integration, both internally within the design function as well as across functions and even across firm boundaries, with suppliers, customers and external design partners. However, some theorists argue that modularity, in particular the standardization of interfaces, is not enough to provide the needed intra- and inter-organizational coordination (e.g. Brusoni and Prencipe, 2001; Sosa *et al*., 2004; Ernst, 2005). Therefore, this thesis proposes different organizational, product design and technological mechanisms that might support successful modularization efforts, including:

Organizational mechanisms: Creating modular systems can be divided into two separate design efforts: initial system level design of the overall product architecture and subsequent detailed design of modules. Especially during the initial system level design efforts, at least some level of cross-functional and cross-boundary integration is necessary to ensure that the resulting modular components can be designed and manufactured independently, as well as meet diverse customer requirements. As a result, successful system-level design of modular systems may require the use of structural organizational arrangements that support cross-functional collaboration and communication, such as cross-functional teams, integrating managers, and co-location. Afterwards, detailed design efforts can, however, can be conducted using standardization as a mechanism. During this stage of design, shared performance targets and interface specifications can be used to coordinate independent team efforts, whereas the teams can rely on mutual adjustment to coordinate internally.

Product design mechanisms: Erixon (1996) proposes that QFD, DFA and DFM should be incorporated in the design of modular sets of products. I suggest to add TRL and FMEA to this set of concurrent engineering design techniques. These practices can support the design of robust modules by forcing the firm to pay attention to customer, manufacturing, assembly, technological maturity, safety and reliability requirements during the design of their products and modules. Whereas these five practices support modularization efforts, these efforts can also play a supporting role themselves. Modularization can be a key ingredient in platform thinking as it helps identify the standardized modules to be part of the product platform and create the standardized interfaces that decouple the product platform modules from the variable components.

Technological mechanisms: The strength of organizational and product design mechanisms can be enhanced through the use of technology. Where computer integrated manufacturing techniques (such as CAD/CAE/CAM) support concurrent engineering by enabling the coordination of design, engineering and manufacturing activities, communication technologies enhance the ease of organizational coordination within and across organizational boundaries.

CHAPTER 5. RESEARCH METHOD

Although modularity theory is characterized by plenty of research interests, the research generally centers around three different research streams, focusing on a) developing constructs and providing a more rigorous understanding of modularity concepts and research, b) how the adoption of modularity influences the coordination of work within and across functions, processes and organizations, and c) proposing and testing the effects of modularity on performance. This thesis takes point of departure in the latter research stream, and has the overall purpose of investigating the following question:

How does product modularity influence the performance of manufacturing firms?

During the 1990s, modularity research was characterized by an abundance of articles that sought to spur practitioner and academic interest by listing many benefits of modularity, based on anecdotal evidence, success stories or prior findings from adjacent fields. As theory progressed, other authors adopted and generalized these context-specific observations (Ernst, 2005), resulting in theory that was overly enthusiastic about the effects of modularity (Magnusson and Pasche, 2014). As a result, a need for a full exploration of the performance effects of modularity arose (Ethiraj, 2007; Campagnolo and Camuffo, 2010), recognizing that practitioners need more than tentative and general propositions in order for them to assess whether modularity is appropriate in their specific setting. Thus, more research is needed that addresses not only what performance effects firms actually experience when adopting modularity, but also embraces organizational practices and contextual variables that affect *how* the use of product modularity influences performance. Therefore, the second research question is:

How do organizational practices and context affect the association between product modularity and the performance of manufacturing firms?

In order to contribute to addressing these questions, this thesis takes it outset in survey research. As noted by Flynn *et al*. (1990, p. 251): "*Anecdotal articles may describe current practices at a single firm, however, systematic data gathering can provide more generalizable evidence about trends and norms in specific populations of firms*". Furthermore, using larger-scale empirical evidence can help testing for associations or hypothesized linkages between predefined concepts and, thus aids in identifying how product modularity affects firm performance, as well as specifying the contexts wherein product modularity indeed works best.

Following the guidelines of Flynn *et al*. (1990), Malhotra and Grover (1998), and Forza (2002), the remainder of this chapter reports the survey studies conducted, according to the structure outlined in Table 10. Based on the literature review reported in the previous chapters, three sub-objectives are identified and presented in Section 5.1. The type of research and investigation that these objectives require is accounted for in Section 5.2. The empirical base of the thesis consists of three surveys. Section 5.3 describes the purpose of each of these three surveys, and details the data collection methods and sampling procedures used. Next, in section 5.4 the measurement instruments are described, with particular emphasis on the operationalization of the measures used in the thesis and the papers.

Table 10 - Information included in reporting the survey research

Main issues	Detailed points	Treated in…
Expected contribution	Research objectives Purpose of the survey research (exploration, description, hypothesis testing)	*Section 5.1* *Section 5.2*
Data collection	Purpose of the surveys (unit of analysis, population fame, respondents) Data collection method and description (time horizon, type of data collection, contact approach, questionnaire construction, participants)	*Section 5.3*
Sample	Sampling approach (probabilistic, random, etc.) Resulting sample (description) Response rate and response bias	*Section 5.3*
Measurement instrument	Types of investigation (causal relationships, differences) Role of the variables (independent, dependent, intervening, moderating) Measures (operational definition of constructs with reference to existing measures)	*Section 5.4*

5.1. SUB-OBJECTIVES

In order to investigate the associations between product modularity, organizational practices and context, and the performance of manufacturing firms, this thesis has three sub-objectives, listed and explained below.

Sub-objective 1: To identify in which organizational settings and environmental contexts the use of product modularity is prevalent.

The creation of modular product portfolios is a resource intensive task, and in order to obtain operational performance benefits from product modularity, it requires a firm to dedicate itself to a particular product architecture for prolonged periods of time. Therefore, environmental characteristics – such as demand, supply, and technological dynamics and predictability, can determine the appropriateness of modularity for the firm. In a very stable and simple environment, it might be too expensive an exercise to implement modularity as firms will not need the flexibility to mix-and-match components according to fluctuating customer demands. In very turbulent or immature environments, locking oneself into a particular product architecture is dangerous, and firms might not be able to reap the long-term benefits of implementing modularity before a new dominant design emerges. Additionally, by pursuing modularity, firms can inadvertently lose their competitive advantage by making it easier for their competitors and suppliers to imitate their product designs.

As a result, modularity might only be appropriate in dynamic, heterogeneous markets and in industries with complex technologies, where competing firms can modularize products in unique ways. In addition to environmental characteristics, the characteristics of the firm itself – such as the firm's size and the type and complexity of the products it produces, can influence whether modularity is an appropriate design philosophy to pursue. Sub-objective 1 aims to investigate these kinds of arguments and develop deeper insight into the association between organizational settings, environmental characteristics and the use of product modularity.

Sub-objective 2: To test how product modularity influences specific operational performance areas.

In the right setting, the adoption of product modularity can provide operational performance advantages for the firm. Increased levels of component sharing can provide typical economies of scale advantages in the manufacturing and purchasing processes, as well as support long-term incremental improvement of purchasing, manufacturing, assembly, and development. Survey based research has also shown modularity to have a positive effect on overall firm and financial performance. The research, however, does not agree on how modularity influences specific performance areas, such as cost, quality and delivery performance, and also is undetermined about the short- and long-term effects of modularity on innovation.

Sub-objective 3: To identify practices that influence how product modularity affects performance, and determine how these practices influence the modularity-performance relationship.

So far, survey research has primarily centered on testing how one specific practice impacts the manner in which modularity influences performance – through integration within and across firm boundaries. However, the research does not agree on the role of integration when it comes to the modularity-performance relationship. Some researchers regard a high level of cross-functional and inter-organizational integration as a prerequisite of successful modularization efforts (Lau *et al*., 2007a; Lau *et al*., 2010; Tu *et al*., 2004; Zhang *et al*., 2014). Other authors, however, view integration as an important mediator in the modularity-performance relationship (Jacobs *et al*., 2007; Ahmad *et al*., 2010; Droge *et al*., 2012; Danese and Filippini, 2013). Yet others focus on the interaction or moderator effects of integration and modularity on performance (Lau *et al*., 2009; Danese and Filippini, 2010; Salvador and Villena, 2013; Hao *et al*., 2015). Thus, there is a need for discussing and testing the relationships between modularity, integrative practices and performance.

However, other manufacturing and/or product development practices might also influence the nature and strength of the performance effects of modularity. Examples of such practices, all enabled by implementing modularity, include delayed differentiation, concurrent manufacturing and loosely coupled product development.

5.2. TYPES OF SURVEY RESEARCH CONDUCTED

The first sub-objective of this thesis aims to explore in which organizational settings and environmental contexts the use of product modularity prevails. This sub-objective calls for descriptive survey research. The primary aim of descriptive survey research is to describe the distribution of a phenomenon in a population (Malhotra and Grover, 1998; Forza, 2002). Even though descriptive research does not develop theory as such, it can prove to be indispensable in early stages of exploring a phenomenon (Malhotra and Grover, 1998). As no or little survey research has developed and tested relationships between the use of modularity and internal and external firm contingencies, this research aims at identifying the settings in which product modularity prevails, and therefore provides a starting point for subsequent explanatory research that tests the effects of different organizational and environmental factors on the modularity-performance relationship.

The second sub-objective seeks to test how product modularity affects well-known performance dimensions. Testing hypothesized relationships between concepts is the primary aim of explanatory survey research (Forza, 2002), which is crucial in theory development. As noted by Doty and Glick (1994, p. 233), there are "*at least three primary criteria that theories must meet: (a) constructs must be identified, (b) relationships among these constructs must be specified, and (c) these relationships must be falsifiable*". As mentioned, much prior conceptual and empirical research has examined the effects of product modularity on performance. Thus, for the second sub-objective of this thesis, the constructs and relationships between the constructs have already been established in prior research. That is, the majority of existing research presumes and has found evidence for product modularity to affect overall performance positively. Sub-objective 2 aims at breaking down operational performance into well-known dimensions, and testing the hypothesis that product modularity affects each of these specific performance dimensions positively.

The third sub-objective is twofold and seeks to both identify practices that have the potential to influence the nature and strength of the modularity-performance relationship and test how these practices affect this relationship. Therefore, theory building *and* theory testing are required. More specifically, based on theory, practices have to be identified that potentially impact the modularity-performance relationship before falsifiable relationships between modularity, these practices and performance can be specified and tested. This has been done in Chapter 4, where different organizational practices that have the potential to influence the modularity-performance relationship were introduced. Section 4.5 concluded that, in small and large batch manufacturing settings, theory proposes the implementation of modularity to allow for late point differentiation, which in turn permits the combination of cost-efficient manufacturing and customer responsiveness. Section 4.6 identified organizational coordination as both an antecedent for successful system level design and iterative development of modular product portfolios, but also highlighted the role product modularity itself can play as a coordination mechanism to facilitate higher levels of integration across functions and organizational boundaries. Section 4.6 also identified other integration mechanisms in the realms of product design, technological systems and organizational design, which may enhance cross-functional coordination further.

5.3. SURVEY DESCRIPTIONS

Three questionnaires form the basis for the descriptive and explanatory survey research conducted in connection with this thesis. This section describes each of these surveys, and details their purpose, target respondents, and data collection processes.

5.3.1. INTERNATIONAL MANUFACTURING STRATEGY SURVEY

The IMSS is an international survey conducted every four to five years by independent research teams from different universities around the globe. It has the primary purpose to study the development and performance effects of different manufacturing strategies and practices. The survey focuses on the dominant activities of single manufacturing and/or assembly plants, and targets the operations, manufacturing or technical manager of the plant. The target population of the IMSS consists of plants with at least 50 employees, belonging to ISIC codes 25-30 (rev. 4). The questionnaire is in English, but is, if necessary, translated into the local language by the national research groups using reliable translation methods (such as double and reverse translation). The IMSS is designed by a group of international scholars, all experts in the area of operations and supply chain management and strategy. The data used in this thesis derives from the sixth round of data collection, conducted in 2013. Prior to the data collection, the survey was pilot tested in a selected group of firms located in the Netherlands, Denmark, Italy, Switzerland, and Germany. In order to increase response rates, ensure that the correct respondent is identified, and receive approval prior to sending the questionnaire, data collection started off with a preliminary phone call. Then, the data was collected using a standardized, self-administered questionnaire, either sent out through e-mail or as a web-survey. The IMSS uses a mix of random sampling and convenience sampling, that is, 77% of the firms contacted were chosen randomly from available databases, whereas 23% where chosen based on convenience. The reason for choosing convenience sampling in addition to random sampling is to ensure responses from firms that previously participated in the survey, and to increase response rates by contacting firms known to the local research team. The individual research teams tested for both non-response and late-response bias, by comparing the size and industry types of the non- and late respondents to the size and industry types of the (other) firms in the sample.

5.3.2. INTERNATIONAL MANUFACTURING STRATEGY SURVEY IN DENMARK

An additional section was included in the standardized IMSS questionnaire sent out to the Danish firms. Designed to support the research reported in this thesis, this section included questions that detailed the performance of, and use of actions programs in, product development and manufacturing. A colleague assessed the quality of the items included in the section, which was furthermore pilot tested by one target respondent. The Danish part of the IMSS data was collected between October 2013 and February 2014, following the approach described in the previous subsection. Firms for the Danish part of the IMSS data collection were identified using a national database (Navn and Numre Erhverv) and all firms with more than 50 employees belonging to ISIC codes 25-30 (Rev. 4) were targeted. Tests for non-response and late response bias revealed that the main sample did not differ from non- or late respondents in terms of size and industry.

5.3.3. SURVEY OF SWEDISH PRODUCT DEVELOPMENT PRACTICES

In addition to the data collected in connection to the IMSS, the thesis also uses data collected in Sweden between November 2014 and February 2015. This data was collected through an online questionnaire. The purpose of this questionnaire was to study the use and performance effects of product development practices in the Swedish manufacturing industry. The survey of Swedish development practices (SPDS) targeted individual manufacturing plants, and focused on how plants organize and manage their product development process, as well as their use of product portfolio planning, lean product development, platform development and product modularization. The questionnaire was designed in collaboration with four Operations Management researchers and based on a previous questionnaire addressing Swedish product development practices. I was primarily responsible for designing the part of the questionnaire addressing the firms' use of product modularity and platforms, as well as designing the measures assessing the environment, performance and strategy of the business unit. The target respondent for the SPDS was the R&D manager (or equivalent) in the firm. The target population of the survey were Swedish manufacturing firms with at least 100 employees, which belong to the rubber and plastic industry, steel and metal industry, metal products industry, computer, electronics and optics industry, electrical appliance industry, other machine hardware industry, engine and trailer industry or other vehicle industry, which, with the exception of the rubber and plastic industry, largely coincides with the IMSS target industries.

5.4. SURVEY SAMPLES

The last three papers that are part of the thesis use the empirical data collected through either the IMSS or SPDS. Paper 3 uses data from the SPDS to describe in which environmental contexts product modularity prevails, and explore whether firms with high product modularity differ from firms with low product modularity in the way they organize product development and in terms of the product development practices they use. Paper 4 uses IMSS data to test whether and how the positioning of the customer order decoupling point affects the performance effects that can be achieved by implementing product modularity (and related practices). Paper 5 also uses IMSS data, this time to test whether internal, supplier and/or customer integration mediate the relationship between the use of product modularity (and related practices) and operational performance.

Except for the regression analyses conducted in relation to paper 5, the statistics that are presented in the three papers have been conducted again, based on slightly different samples than those presented in these three papers for reasons explained below. In addition, none of the papers use data from the Danish IMSS data collection. Therefore, this section details the samples that will form the basis for the descriptive statistics reported in this thesis, and explain how these samples differ from the samples used in papers 3 to 5.

5.4.1. THE IMSS SAMPLE

From the 7167 firms originally contacted, a total of 2586 firms agreed to participate in the IMSS, of which a total of 931 actually responded – resulting in a final response rate of 36% of the firms that agreed to participate and 13% of all the firms that were contacted. These 931 responses form the basis for the statistics conducted in paper 4 and 5. However, it should be kept in mind that in these papers, the only data that actually are used for the statistical tests conducted are those from plants that have responded to the questionnaire items of interest in the respective papers. In paper 4, data from 639 firms were used, which had indicated that they had implemented Design for Variety and used one of four customer order decoupling points for at least 60% of their production volume. In paper 5, data were used from the 702 firms that responded to the variables of interest in the paper.

With hindsight, however, the Indian data appeared unreliable, and was discarded from the sample used in this thesis. Furthermore, three responses from the U.S. were left out, since they had a questionnaire completion rate of below 50%. Therefore, in Chapter 6, only 837 responses form the basis for the statistical tests conducted and reported. Table 11 describes the sample demographics of these 837 firms. It should be kept in mind, however, that the final sample may differ slightly from test to test, dependent on which respondents provided a response for the variables at hand.

For the Danish IMSS sample, a total of 310 firms were contacted, of which 129 firms agreed to participate. The final sample obtained in Denmark consisted of 39 firms that had completed at least 60% of the entire questionnaire – resulting in a response rate of 30% of the firms that agreed to participate and 13% of all the firms that were contacted. In the Table 12, the characteristics of the Global and Danish IMSS samples are detailed; the data for the IMSS-DK sample are in bold.

Table 11 - IMSS demographics

Region	**N**	**%**
Americas	106	13
Asia	252	30
Northern Europe	131	16
Western Europe	123	15
Southern Europe	111	13
Eastern Europe	114	14
Total	837	

Table 12 - Characteristics of the Global and Danish IMSS sample

ISIC code	N		%	
25 Metal Products	271	**7**	32	**18**
26 Electronics	96	**7**	11	**18**
27 Electrical	135	**3**	16	**8**
28 Machinery	215	**22**	26	**56**
29 Motor Vehicles	80	**0**	10	**0**
30 Other transport	40	**0**	5	**0**
Total	837	**39**		

# of employees	N		%	
50-99	183	**6**	22	**15**
100-249	194	**13**	23	**33**
250-499	126	**8**	15	**21**
500-999	100	**5**	12	**13**
1000-4999	139	**3**	17	**8**
≥ 5000	94	**4**	11	**10**
Total	836	**39**		

5.4.2. THE SPDS SAMPLE

From the Swedish Postal Address Register, a total of 478 firms were identified that fulfilled the aforementioned sampling criteria. From these, 148 firms were later excluded as they did not have any internal R&D function. The questionnaire was sent out to a total of 315 business units, of which 262 had agreed to participate and 52 received the questionnaire without any prior promise of participation. A total of 160 firms responded, of which 13 firms were excluded as they completed less than 50% of the questionnaire and 6 firms were excluded because they did not have any internal manufacturing. The final sample used in this thesis consists of 141 firms. The response rate was 54% of the firms that agreed to participate and 30% of all the firms that were contacted.

Here again, there are some differences between these figures and percentages and the ones reported in, in this case, paper 3. The sample used in that paper consisted of 138 firms. From the original 160 firms, 15 were excluded, as they completed less than 70% of the questionnaire. In addition, 7 respondents were excluded, which did not answer to at least 5 out of the 7 items of the independent research variables. The sample in paper 3 does, however, include the firms that do not have internal manufacturing.

Table 13 - Characteristics of the SPDS sample

Product type	N	%
Semi-manufacture	38	27
End-products	102	73

Product type	N	%
Consumer	28	20
Industrial	112	80

Employees in PD	N	%
5 or less	31	22%
6-10	25	18%
11-25	36	26%
26-50	19	14%
50-100	7	5%
≥ 100	20	14%
Total	138	

5.4.3. COMPARISON OF SAMPLE CHARACTERISTICS

Tables 11 to 13 describe key characteristics of these final samples. Compared to other surveys that have tested the effects of product modularity on operational performance, the IMSS and SPDS target a broader spectrum of industries. For instance, the first paper to ever test the effects of product modularity, does so based solely on evidence the U.K. and U.S. home appliance industries to find that the use of modularity-based manufacturing practices is positively related to model variety (Worren *et al*., 2002). The automotive industry has also been a great source of evidence for survey research on the operational performance effects of product modularity. In particular, evidence from 57 tier one suppliers in the U.S. automotive industry has been used to verify that product modularity has a positive influence on cost, quality, flexibility and time performance (Jacobs *et al*., 2007), manufacturing agility (Jacobs *et al*., 2011) as well as support and delivery performance (Droge *et al*., 2012). Parente *et al*. (2011) also use evidence from the automotive industry. That paper uses data collected from 111 firms in the Brazilian auto industry to establish a link between product modularity and new product performance.

A group of authors that has been very active in researching the effects of product modularity are Lau, Yam and Tang, who use evidence from 251 firms in the Hong Kong electronics, plastics and toys industries to establish that product modularity has a positive influence on flexibility and customer service performance (Lau *et al*., 2007a; 2007b; 2009) as well as product innovativeness (Lau *et al*., 2009). Later, Lau *et al*. (2011) also verify the positive association between product innovativeness and product modularity based on data from 115 firms within the Hong Kong electronics industry. Evidence from the electronics, machinery and transportation industries in eight different countries is used to verify that product modularity positively influences new product development performance (Danese and Filippini, 2010; 2013), indirectly influences overall operational performance (Ahmad *et al*., 2010), and has a significant impact on manufacturing unit costs, product functionality and product durability (Salvador and Villena, 2013). The only group of authors who truly encompass a broad set of industries in their analyses are Vickery *et al*. (2015), who find that product modularity facilitates the use of product platforms, which increases manufacturing flexibility and, indirectly, the firm’s ability to frequently and timely launch new products.

The importance of including a broad set of industries is evident from the ongoing discussion on how modularity influences the organization of work. While in some industries – such as the electronics and bicycle industries – the wide use of modularity has been accompanied by the vertical disintegration of supply chains (Langlois and Robertson, 1992; Baldwin and Clark, 2000; Galvin and Morkel, 2001), other industries, such as the automotive, aircraft engine and chemical engineering industries, have not experienced similar effects (Brusoni and Prencipe, 2001; Genba *et al*., 2005; Ro *et al*., 2007). Finally, most research, so far, has been based on limited geographical evidence from the U.S., specific Asian areas, the U.K. or Brazil. The only exceptions are the articles based on the High Performance Manufacturing survey (e.g. Ahmad *et al*., 2010; Danese and Filippini 2011; 2013;

Salvador and Villena, 2013), which, similar to the IMSS and SPDS, include evidence from other, e.g. the Scandinavian, countries.

5.5. THE MEASUREMENT INSTRUMENTS

The findings presented in the next chapter are based on the regression analyses reported in paper 5 and independent t-tests conducted on the IMSS, IMSS-DK and SPDS samples detailed in the previous section. All statistical tests conducted in the papers and in the thesis use one of two independent variables, dependent on the whether the underlying pool of data derives from the IMSS or the SPDS. These two independent variables are explained in the following two sections, after which the measures and type of tests conducted to answer the three sub-objectives in the thesis are outlined.

5.5.1. PRODUCT MODULARITY IN THE SPDS

To recall, this thesis argues it is important to distinguish between the *characteristics* and *product effects* of product modularity. It defines product modularity based on two characteristics, i.e. as a function of the degree to which the firm uses standardized modules and interfaces. Increasing the degree to which the modules and their interfaces are standardized, accommodates certain *product effects,* including loose coupling, component sharing, component separability, and component combinability.

Existing survey research has adopted a variety of items to measure the degree to which the firm uses product modularity. Overall, however, the research often departs from the *product effects* of modularity. This means that reflective, rather than formative items, are used to measure product modularity. As evidenced in Table 14, two reflective items included in most measures of modularity are 1) the degree to which designs, modules, subassemblies, components or parts are reused, carried-over, and shared across products (*component sharing)* and 2) the degree to which options, features, parts and modules are interchangeable and can be easily configured, reassembled, reconfigured and mixed and matched to create product variants (*component combinability)*. Some articles also measure the ability to make localized changes to components without redesigning others *(loose coupling)* and the degree to which products can be decomposed in separate modules (*component separability).* In addition, some authors use items that assess whether features, functions and options can be added to standard products, base units or core technologies (e.g. Duray, 2004; Tu *et al*., 2004; Howard and Squire, 2007; Liao, 2010; Thatte, 2013: Vickery *et al*., 2015). It can, however, be argued that this last pool of items only measures one particular type of modularity, i.e. bus modularity, where product variants are created by adding different (sets of) components, options, features or functions to a common product body (Ulrich, 1995; Ulrich and Eppinger, 2012)

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Table 14 - Measures used in survey research (extended from paper 1)

Worren et al., 2002; Lau et al. 2007a[1]; 2007b[1]; 2009[1]; 2010[1]; 2011; Parente et al., 2011[2]

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
Products' components are standardized (1)
Overall our business unit adopts a high degree of modularity in production (2)

Duray 2004; Howard and Squire, 2007

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

Tu et al., 2004; Liao, 2010; Thatte, 2013

Our products use modularized design
Our products share common modules
Our product features are designed around a standard base unit
Product modules can be reassembled into different forms
Product feature modules can be added to a standard base unit

Jacobs et al. 2007; 2011; Droge et al., 2012

Modularity: The process of developing interchangeable parts across products that can be reconfigured into a wide variety of end products
Standardization: The use of standard procedures, materials, parts, and/or processes for designing and manufacturing a product

Bush et al, 2010

Product parts and assemblies are shared across products
Products have a modular design
New product offerings reuse the designs of existing components
Our product offerings integrate components from multiple suppliers
Our product offering consists of components that can be mixed and matched in a variety of configurations

Ahmad et al., 2010[3], Danese and Filippini 2010; 2013[3], Salvador and Villena, 2013[3]

Our products are modularly designed, so they can be rapidly built by assembling modules
We have defined product platforms as the basis for future product variety and options (3)
Our products are designed to use many common modules
When we make two products that differ only by a specific feature, they generally require only one different subassembly/component (3)
We do not use common assemblies and components in many of our products (reverse)

Hao et al., 2015

Highly interoperable
Stable, well-defined interfaces
Well-understood interdependencies
Minimal unnecessary interdependencies

Vickery et al., 2015

For our products, functions can be directly added or deleted by adding or removing components
The interfaces of our product components are designed to accept a variety of components
Our products are designed to be easily reconfigurable

Note: *Differences between items included in measures used in multiple articles are indicated with a number after the item, which specifies in which the article the item is used.*

Table 15 - SPDS product modularity items

Question: To what degree do the following statements describe your main products?

Scale: from 1 (not at all) to 7 (to a very high degree)

Items:

Our products are divided into separate modules	*Worren et al., 2002* *Lau et al. 2007a; 2007b; 2009; 2010; 2011* *Parente et al., 2011*
We can make changes to a module without other modules need to be reconstructed	*Worren et al., 2002* *Lau et al. 2007a; 2007b; 2009[1]; 2010; 2011* *Parente et al., 2011*
Our modules can be combined in several ways to create product variants	*Bush et al., 2010*

As shown in Table 15, the SPDS uses three out of the four product effects to measure modularity. These three items reflect the degree to which the firm's main product can be separated into modules (component separability), the degree to which the firm can make changes to a module without having to reconstruct others (loose coupling) and the degree to which modules can be combined in several ways to create product variants (component combinability). The first two of these items are similar to items used by Worren *et al*. (2002), Lau *et al*. (2007a; 2007b; 2009; 2010; 2011) and Parente *et al*. (2012). The last item in the SPDS's operationalization of product modularity is similar to the last item used by Bush *et al*. (2010) and the modularity item used by Jacobs *et al*. (2007; 2011) and Droge *et al*. (2012). Component sharing was not included as this is not only an effect of modularity but also of platform design, which is a practice also measured in the SPDS questionnaire.

In order to conduct the t-tests reported in Chapter 6, the SPDS sample is divided into two subsamples according to the sample firms' average score on the three product modularity items. Firms with an average score equal to or lower than five are categorized as having a low degree of product modularity and firms with an average score higher than five are categorized as having a high degree of product modularity.

5.5.2. DESIGN FOR VARIETY IN THE IMSS

The independent variable that forms the basis for papers 4 and 5 as well as the additional IMSS based t-tests is a one-item variable, which measures the degree to which the focal firm uses design practices such as platform design, standardization and modularization, design for manufacturing (DFM), and design for assembly (DFA) (see Table 16). Paper 5 explains how these practices correspond: "*Design-for-Variety (DFV) is a group of design practices, including modularization, platform-based development, design for manufacturing (DFM) and design for assembly (DFA), which are all aimed at managing and minimizing the negative impact of external demands for product variety on internal operational* *performance. Common to all these practices is that they seek to minimize internal complexity by simplifying the overall product design and promoting the standardization of components, interfaces and assemblies."* (Paper 5, p. A68). The similarities and differences between these practices are further explained in papers 4 and 5.

To conduct the t-tests reported in Chapter 6, the IMSS sample is divided into subsamples according to their score on the DFV item. Firms with a score of three or lower are categorized as having a low use of DFV practices, firms with a score of four or higher are categorized as having a high use of DFV practices. Moreover, the use of DFV practices is an independent variable in paper 5, which employs mediated regression to test whether internal and external integration mediates the relationship between the use of DFV practices and operational performance.

Table 16 - IMSS DFV item

Question: Indicate the current level of implementation of action programs to coordinate your new product development and manufacturing processes, related to
Scale: from 1 (none) to 5 (high)
Items: Design integration between product development and manufacturing through e.g. platform design, standardization and modularization, design for manufacturing, design for assembly

5.5.3. ORGANIZATIONAL CONTEXT AND SETTINGS

In order to support future explanatory research that examines the effects and effectiveness of modularity in different environmental and organizational settings, exploratory research is needed to identify contextual variables which are most likely to dictate the appropriateness of product modularity. In order to achieve this insight, t-tests, reported in Chapter 6, are used to determine whether firms with *high* product modularity differ from firms with *low* use of modularity in terms of their environmental and organizational characteristics.

To capture the external environment in which the firm operates, the IMSS and SPDS use the questions and items listed in Tables 17 to 19. Both surveys include traditional items to assess the level of competition and dynamics experienced by the firm (Roth *et al.*, 1998).

The IMSS measures the level of competition the firm experiences by taking point of departure in the competitive forces proposed by Porter (1979). In addition to measuring the level of competitive rivalry within the industry, the IMSS therefore includes items addressing the entry barriers and the threat of substitute products, as well as the bargaining power of suppliers and customers (cf. Porter, 1979; 2008). In order to characterize the firm's marketplace, the IMSS considers the number of customer segments the firm addresses (market span), the number of competitors within the marketplace (market concentration) as well as market growth. Furthermore, the IMSS asks the respondents to evaluate the degree to which they experience technological change, and to assess environmental dynamics through items that measure the degree to which their firm's own demand, manufacturing volume, product mix and supply requirements fluctuate, and items that measure the frequency at which the firm's products and supplier parts/component have to be modified.

Table 17 - SPDS environmental items

Question: What characterizes your market situation?

Scale: from 1 (not at all) to 7 (to a very high degree)

Items:
Variation in demand
Demand for product customizations
Price pressure
Competitiveness
Quick technological shifts

Table 18 - IMSS environmental items

Question: How do you perceive the following characteristics of the environment in which your business unit operates? ‘

Items:	**Scale:**	
Market size	1: Declining rapidly	5: Growing rapidly
Rate of technological change	1: Very low	5: Very high
Market span	1: Few segments	5: Many segments
Market concentration	1: Few competitors	5: Many competitors
Competitive rivalry within industry	1: Very low	5: Very high
Market entry	1: Closed to new players	5: Open to new players
Threat that your product will become substituted	1: Very low	5: Very high
Bargaining power of suppliers	1: Very weak	5: Very strong
Bargaining power of customers	1: Very weak	5: Very strong

Table 19 - IMSS environmental dynamics items

Question: To what extent do you agree with the following statements?

Scale: from 1 (not at all) to 5 (to a very high degree)

Items:
Your demand fluctuates drastically from week to week.
Your total manufacturing volume fluctuates drastically from week to week.
The mix of products you produce changes considerably from week to week.
Your supply requirements (volume and mix) vary drastically from week to week.
Your products are characterized by a lot of technical modifications.
Your suppliers frequently need to carry out modifications to the parts/components they deliver to your plant.

The SPDS includes two items asking the respondents to evaluate the degree to which they experience competitive rivalry and price pressures (reflecting the level of competition faced by the firm) and two items that evaluate the degree to which the firm experiences variation in demand and technological shifts (reflecting the level of dynamics the firm experiences). As product modularity is often linked to mass customization (da Silveira *et al*., 2001), the SPDS also enquires about the degree to which the firm experiences demand for customization.

To identify the organizational contexts in which the use of product modularity prevails, t-tests are used to compare the low and high use subsamples in terms of industry type, plant size, product type, and product complexity. To identify the type of industry the firms belong to, the respondents of the IMSS were asked to choose the industry code that best describes the activities of their business unit. Based on the fourth revision of the International Standard Industrial Classification (ISIC Rev. 4), respondents could choose from six different industries (Table 20). To evaluate plant size, the respondents were asked to indicate the number of employees their firm had in 2012. To identify the types of products produced by the plant, the respondents were asked to indicate the percentage of sales based on a) parts and components, b) assembled products, and c) services (the numbers had to add up to 100%). In addition, they were asked to evaluate the complexity of their dominant activity (see Table 21). Product complexity can be defined as "*A state of processing difficulty that results from a multiplicity of, and relatedness among, product architectural design elements*" (Closs *et al*., 2008, p. 591). Correspondingly, the respondents were asked to assess the number of parts/materials in their products and indicate the depth of their bill of materials. In addition, they were asked to assess the number of steps/operations in their production processes, which gives a picture of how difficult it is to process the firm's products.

Table 20 - IMSS industry items

Question: Please tick the industry code that best describes the activities of your business unit

Items:

25	Manufacture of fabricated metal products, except machinery and equipment
26	Manufacture of computer, electronic and optical products
27	Manufacture of electrical equipment
28	Manufacture of machinery and equipment not elsewhere classified
29	Manufacture of motor vehicles, trailers and semi-trailers
30	Manufacture of other transport equipment

Table 21 - IMSS product complexity items

Question: How would you describe the complexity of the dominant activity

Items:	**Scale:**
Parts/materials and bill of materials	1: Very few parts/materials, one-line bill of material 5: Many parts/materials, complex bill of material
Steps/operations required	1: Very few steps/operations required 5: Many steps/operations required

5.5.4. EFFECTS ON OPERATIONAL PERFORMANCE

In order to determine the effects of product modularity on firm performance, this thesis uses independent samples t-tests and regression analysis. The t-tests are used to determine whether there is a difference in performance between firms with a *low* use of product modularity and firms with a *high* use of product modularity. Regression analysis is used in paper 5 to determine whether there is a positive relationship between the use of product modularity and key performance areas. All three surveys were used to determine the operational performance effects of product modularity. As detailed in Tables 22 to 24, all three surveys measured operational performance by asking firms to evaluate their current performance relative to their major competitor(s).

The IMSS uses well known measures of operational or manufacturing performance within the areas of quality, delivery, flexibility, cost, and new product introduction (*cf*. Lau *et al.*, 2007a; Ahmad *et al*., 2010), but also includes measures of service (*cf*. Lau *et al.*, 2007a) and time performance (*cf*. Jacobs *et al.*, 2007). Factor analyses further detailed in paper 5 show that the measures used in the IMSS reflect five underlying variables, denoted quality, cost and speed, flexibility, service, and delivery. The SPDS uses similar measures, but instead of focusing on the cost and speed of *manufacturing and ordering* like the IMSS does, this survey focuses on the cost and speed of *product development*. In addition to the measures listed in Table 23, the SPDS also measures the firm's product variety and innovativeness. Product variety is assessed by asking the respondents to indicate, on a scale from 1 (significantly less) to 7 (significantly more), the number of product variants in their firm's product portfolio compared to that of their major competitors. Innovativeness is assessed by asking firms to indicate (as a percentage) how large a portion of their revenue is based on products/services introduced the last five years.

The IMSS-DK focuses on the performance of the firm's product development and production processes as well as the firm's manufacturing batch size, product variety and innovativeness. The firm's innovativeness is indicated using a similar measure as used in the SPDS. The IMSS-DK, however, delineates between the firm's ability to create and sell entirely new products and its ability to use existing product designs to create and sell new product variants/improvements. Thus, in order to measure firm innovativeness, respondents were asked to indicate the percentage of sales based on sales of a) new product launched within the last three years, b) product variants and product improvements launched within the last three years, c) existing products launched more than three years ago (the numbers had to add up to 100%). Similar to the SPDS, the IMSS-DK also measures product development cost and speed, but again delineates between the cost and time connected to developing new products and the cost and speed of developing new product variants and product improvements.

Table 22 - IMSS performance items

Question: How does your current performance compare with that of your main competitor(s)?

Scale: from 1 (much lower) to 5 (much higher)

Factor:	**Items:**
Quality	Conformance quality Product quality and reliability
Cost and Speed	Ordering costs Manufacturing costs Procurement lead time Manufacturing lead time
Flexibility	Mix flexibility Volume flexibility Product customization ability
Service	Customer service quality Product assistance and support
Delivery	Delivery reliability Delivery speed
Other	Product introduction ability

Table 23 - SPDS performance items

Question: How does the performance of your firm compare to your main competitors?

Scale: from 1 (much worse) to 7 (much better)

Items:
Product performance
Quality
Durability
Product development costs
Product development lead time
Product customization
Profit margin

Table 24 - IMSS DK performance items

Question: How does your […..] compare with that of your main competitor(s)?

[…]:	**Items:**	**Scale:**
Product development performance	New product development lead time Product variant development lead time New product development costs Product development costs	1: Much lower 5: Much higher
Assembly performance	Assembly lead time Assembly costs	1: Much lower 5: Much higher
Product variety and batch size	Product variety Manufacturing batch size	1: Much larger 5: Much smaller

5.5.5. ORGANIZATIONAL PRACTICES

Three groups of practices and/or organization characteristics were identified that could influence the appropriateness of modularity. These include 1) the organization of product development and use of product development practices, 2) the type of fabrication and assembly process used and the positioning of the customer order decoupling point (CODP), and 3) the level of internal integration with sales and purchasing and external integration with suppliers and customers.

Product development organization and practices

To assess whether the organization of development and certain product development practices influence the strength and nature of the performance effects of product modularity, data from the SPDS and IMSS-DK was used (the IMSS does not enquire about these items). Since the SPDS and IMSS-DK data does not find a significant association between product modularity and performance, independent t-tests were only used to assess whether firms with high product modularity differ from firms with low modularity in terms of their product development organization and practices. Table 25 shows the SPDS measures used to determine how a firm organizes its product development; Table 26 shows which product development practices were included in the SPDS.

Table 25 - SPDS product development organization items

Items:	**Scale:**
How large a portion of product development a cross-functional team conducts	1: No amount 7: Entirely
How often project management is physically collocated	1: Never 7: Always
The degree to which the business units projects are structured according to a formal product development process	1: Very low degree 7: Very high degree
Use of outsourcing of product development work	Percentage outsourced

Table 26 - SPDS product development practices items

Question: How important is the following for your product development work
Scale: from 1 (Not important) to 7 (Very important)
Items: Failure mode and effects analysis (FMEA) Design for assembly (DFA) Quality function deployment (QFD) Rapid prototyping (e.g. SLA/SLS) Agile work (e.g. scrum) Defined stages and/or gates (e.g. Stage gate) TRL classification (technological readiness level)

The operationalization of these measures is treated in paper 3: "*To assess how product development is organized, we measured the degree to which the product development process is formalized, co-located and handled by cross-functional* *teams, all reflecting different ways to achieve integration within and between functions (Child, 2005). In addition, we also measured the degree to which the company has used outsourcing, which is a popular mode of organizational restructuring (Child, 2005). To identify which product development practices are used within the organization, we asked the respondents to identify the degree to which their firm uses 1) techniques and methods for approaching product development work (e.g. FMEA, DFA, QFD, Rapid Prototyping, and TRL classification) and 2) managerial practices for product development (e.g. agile work procedures and defined stages and/or goals)"* (Paper 3, p. A39).

Table 27 - IMSS DK action programs items

Question: Indicate the current level of implementation of action programs related to product development and manufacturing

Scale: from 1 (None) to 5 (High)

Items
<u>Group technology (</u>the grouping of components according to similarities in processing requirements and using dedicated cells of machinery and teams to manufacture the groups of components)
<u>Parallel product development</u> (dividing design tasks so that autonomous teams design, develop and experiment with independent components in parallel)

According to Ulrich (1995), adopting a modular architecture allows firms to divide their development organization into specialized groups, where detailed design activities can take place almost independently and in parallel. To test this, the IMSS-DK included a measure, denoted "parallel product development", which enquires about the firm's ability to divide its design tasks so that autonomous teams design, develop and experiment with independent components in parallel. The IMSS-DK also enquires about the firm's implementation of group technology, even though group technology is a manufacturing practice, rather than a product development practice. Product modularity allows the firm to organize its production into specialized groups with a narrow focus (Ulrich, 1995), where independent components can be grouped and produced and tested separately (Ulrich and Tung, 1991). Group technology provides the basis for that Thus, respondents were asked about the degree to which they implemented group technology, operationalized as the grouping of components according to similarities in processing requirements and using dedicated cells of machinery and teams to manufacture the groups of components (Droge *et al*., 2012). Both IMSS-DK measures are shown in Table 27.

Customer order decoupling point

In contrast to the other two questionnaires, the IMSS data does provide evidence for a positive association between the use of DFV practices and performance. Therefore, in addition to the independent t-tests that investigate how firms with high modularity differ from firms with low modularity in terms of CODP, additional independent t-tests were conducted to assess differences in performance. To assess which CODP(s) the firm uses, respondents were asked to indicate the percentage of customer orders that are a) designed/engineered to order (DTO) b) manufactured to order (MTO) c) assembled to order (ATO) and d) produced to stock (PTS) (the numbers had to add up to 100%). To assess whether the positioning of the CODP has an impact on the relationship between the use of DFV and performance, the sample was divided into four different groups according to whether they primarily use DTO, MTO, ATO, and PTS. Firms indicating that at least 60% of the orders are handled using only one of these CODPs were assigned to the respective groups, the other firms were discarded. Then, t-tests were used to test for differences between firms with a low use of DFV and firms with a high use of DFV within the performance dimensions specified in the previous section. The resulting subsamples are shown in Table 28.

Table 28 - IMSS subsamples according to CODP

	Low DFV	High DFV	Total
DTO	63	37	**100**
MTO	186	98	**284**
ATO	68	65	**133**
PTS	47	33	**80**

Internal and external integration

To capture the degree to which the firm has implemented internal and external integration, the IMSS uses the measures specified in Table 29. Factor analyses, further detailed in paper 5, show that these measures reflect three underlying variables denoted internal, supplier and customer integration. Paper 5 also reflects on the operationalization of these variables: "*Internal integration is operationalized using two items each for integration with purchasing and sales, respectively, namely 1) sharing information and 2) joint decision making. These items go back to Ellinger et al. (2000) and have also been used by e.g. Giménez and Ventura (2006) and Yang et al. (2016). Following Ellinger et al. (2000), Frohlich and Westbrook (2001) and Droge et al. (2012), external integration includes both upstream supplier integration and downstream customer integration. Supplier integration was studied by Handfield and colleagues (e.g. Ragatz et al., 1997; Handfield et al., 2000; Petersen et al., 2005). Akao (1990) and Lengnick-Hall (1996), amongst others, showed the importance of customer integration. Four items were used to operationalize both forms of external integration. Sharing information and joint decision making were adapted from Ellinger et al. (2000), Giménez and Ventura (2006), Golini and Kalchschmidt (2009), Vanpoucke et al. (2014) and He et al. (2014). Developing collaborative approaches was adapted from Handfield et al. (2000) and Golini and Kalchschmidt (2009). Previously proposed by Golini and Kalchschmidt (2009) and based on, amongst others, Das et al. (1997) and Disney and Towill, 2003, system coupling is a new item. All three constructs were validated in a recent paper by Yang et al. (2016). Sancha et al. (2015) validated the supplier integration scale.*" (Paper 5, p. A81). In addition to the t-tests, which assess the difference in integration levels between firms with low use of DFV and firms with high use of DFV, paper 5 uses mediated regression to test if internal, supplier and customer integration mediates the relationship between the use of DFV practices and performance.

Table 29 - IMSS integration items

Question: Indicate the current level of implementation of, action programs related to internal integration /external integration

Scale: From 1 (None) to 5 (High)

Area:	**Items:**
Internal	Sharing information with purchasing department (about sales forecast, production plans, production progress and stock level) Joint decision making with purchasing department (about sales forecast, production plans and stock level) Sharing information with sales department (about sales forecast, production plans, production progress and stock level) Joint decision making with sales department (about sales forecast, production plans and stock level)
Supplier	Sharing information with key suppliers (about sales forecast, production plans, order tracking and tracing, delivery status, stock level) Developing collaborative approaches with key suppliers (e.g. supplier development, risk/revenue sharing, long-term agreements) Joint decision making with key suppliers (about product design/modifications, process design/modifications, quality improvement and cost control) System coupling with key suppliers (e.g. vendor managed inventory, just-in-time, Kanban, continuous replenishment)
Customer	Sharing information with key customers (about sales forecast, production plans, order tracking and tracing, delivery status, stock level) Developing collaborative approaches with key customers (e.g. risk/revenue sharing, long-term agreements) System coupling with key customers (e.g. vendor managed inventory, just-in-time, Kanban, continuous replenishment) Joint decision making with key customers (about product design/modifications, process design/modifications, quality improvement and cost control)

5.6. SUMMARY - RESEARCH METHOD

The thesis uses survey research to decipher how product modularity influences the performance of manufacturing firms, and to detect how organizational practices and context affect this association. More specifically, data from three surveys are used to answer the three sub-objectives:

- *SO 1: To identify in which organizational settings and environmental contexts the use of product modularity is prevalent.*
- *SO 2: To test how product modularity influences specific operational performance areas*
- *SO 3: To identify practices that influence how product modularity affects performance (part 1), and determine how these practices influence the modularity-performance relationship (part 2)*

The survey with the smallest sample, the IMSS DK, is focused on the performance of, and use of action programs in, product development and manufacturing. As a result, its data is used to determine whether firms with a high use of product modularity (and related practices) differ from other firms in their product development performance, assembly performance, product variety and batch size (SO 2), and in their use of group technology and parallel product development (SO 3, part 1).

The SPDS is primarily concerned with product development practices and performance, but also encompasses items that touch upon the environmental context of its target population. Therefore, this survey provides partial answers to each of the three sub-objectives. More specifically, the SPDS helps explore how firms with high use of product modularity differ from others in 1) the degree to which the firms experience environmental dynamics, uncertainty and demand for product customization (SO 1), 2) their performance in the areas of quality, product development, product customization and variety, innovativeness and profit (SO 2), and 3) their organization of product development and use of methods, techniques and managerial practices in product development (SO 3, part 1).

The survey that by far provides the most data for answering the three sub-objectives is the IMSS. In comparison to other surveys that have tested the effects of product modularity on operational performance, the IMSS encompasses a larger sample, a broader spectrum of industries as well as a larger geographical range. It also encompasses a wide range of items, relevant for each of the three sub-objectives. Not surprisingly, this survey therefore provides the backbone for answering the research questions of this thesis. In regards to SO 1, the IMSS helps identify the organizational setting the use of product modularity is prevalent in, through items addressing industry type, plant size, product type, and product complexity. Items concerning the strength and power of competitive forces (Porter, 1979) as well as items addressing key marketplace characteristics (span, concentration and growth) and key dynamic characteristics (rate of technological change, fluctuation in demand, volume, mix, degree of technical modifications), moreover, help specify the environmental contexts in which modularity is prevalent (SO 1). To address SO 2, the IMSS provides insight into differences between subsamples' performance in the areas of quality, cost and speed, flexibility, service, delivery and product introduction ability. As Chapter 6 will detail, tests conducted on the IMSS data show a significant and positive relation between the use of product modularity and these performance dimensions. Therefore, in contrast to the other two surveys, the IMSS data is not only used to identify practices that influence the modularity-performance relationship (SO 3, part 1), but also to provide insight into *how* these practices influence performance (SO 3, part 2). In particular, IMSS data is used to test how the positioning of the COPD and how internal, supplier and customer integration influence the product modularity-performance relationship.

CHAPTER 6. FINDINGS

This chapter is structured according to the sub-objectives of this thesis. Section 6.1 identifies the organizational settings and contexts in which the use of modularity prevails. Section 6.2 reports the effect product modularity has on specific performance objectives. Section 6.3 identifies practices that might influence the strength and nature of the performance effects of product modularity, and determines how 1) the positioning of the CODP and 2) degree of supplier, customer and internal integration influence the modularity-performance relationship. This chapter primarily reports the results the independent t-tests conducted on the basis of the IMSS, IMSS-DK and SPDS samples described in the last chapter. The results of these independent t-tests are reported according to Figure 5. The first column describes the dependent variable at hand; the next two specify the size of the subsamples, followed by two columns reporting the subsample means. The result of the t-test is reported by indicating the difference between the two subsample means, as well as the significance of the t-test and the respective effect size. Significant t-tests *(p* < 0.05) are highlighted with grey. Cohen's *d* measure is used to determine the effect size, where *d* = 0.02 constitutes a small effect, *d* = 0.05 a medium effect and *d* = 0.08 a large effect.

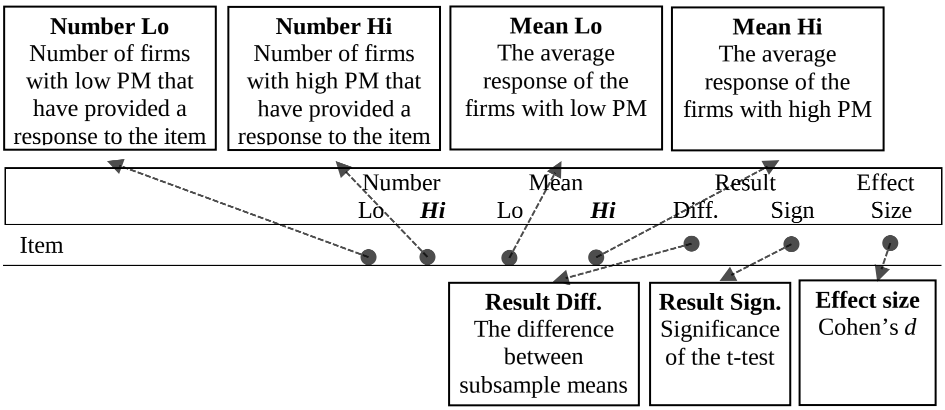

Figure 5 - Interpreting t-test results

6.1. ORGANIZATIONAL SETTINGS AND CONTEXTS

To identify in which organizational settings and contexts the use of product modularity prevails, this section takes its outset in the tests conducted in paper 3 and additional t-tests. Paper 3 uses SPDS data to compare the environmental characteristics of firms with high product modularity to the characteristics of firms with low product modularity. T-tests conducted based on the IMSS compare the subsamples in additional environmental characteristics, as well as firm and product characteristics.

Table 30 - IMSS environmental results

	Sample		Mean		Result		Effect
	Lo	***Hi***	Lo	***Hi***	Diff.	Sign	Size
Market size	499	***305***	3.14	***3.34***	0.20	0.001	(0.25)
Rate of technological change	498	***304***	3.12	***3.47***	0.36	0.000	(0.37)
Market span	496	***303***	3.27	***3.47***	0.20	0.007	(0.20)
Market concentration	498	***303***	3.37	***3.56***	0.19	0.017	(0.17)
Competitive rivalry	496	***304***	3.79	***3.94***	0.16	0.021	(0.17)
Market entry	497	***304***	2.94	***2.91***	- 0.03	0.669	(0.03)
Substituted products	491	***302***	2.93	***3.00***	0.07	0.389	(0.06)
Bargaining power of suppliers	492	***301***	3.04	***3.17***	0.13	0.043	(0.15)
Bargaining power of customers	494	***302***	3.62	***3.77***	0.15	0.027	(0.16)

Table 31 - IMSS environmental dynamics results

	Number		Mean		Result		Effect
	Lo	***Hi***	Lo	***Hi***	Diff.	Sign	Size
Demand	491	***300***	2.68	***2.77***	0.08	0.328	(0.08)
Manufacturing	489	***300***	2.51	***2.51***	0.01	0.931	(0.01)
Product mix	487	***299***	2.79	***2.88***	0.09	0.279	(0.08)
Supply	488	***300***	2.67	***2.71***	0.04	0.651	(0.03)
Technical modification	489	***299***	2.72	***2.79***	0.07	0.440	(0.06)
Supplier modifications	490	***300***	2.25	***2.35***	0.10	0.224	(0.09)

Table 32 - SPDS environmental results

	Sample		Mean		Result		Effect
	Lo	***Hi***	Lo	***Hi***	Diff.	Sign	Size
Variation in demand	80	***53***	4.75	***4.77***	0.02	0.925	(0.02)
Product customization demand	80	***53***	4.94	***5.64***	0.70	0.003	(0.53)
Price pressure	80	***54***	5.69	***5.54***	- 0.15	0.474	(0.13)
Competitiveness	80	***54***	5.55	***5.50***	- 0.05	0.799	(0.04)
Quick technological shifts	80	***54***	3.18	***3.20***	0.03	0.899	(0.02)

The largest contextual difference between the IMSS subsamples is related to the rate of technological change experienced by the firms (Table 30). Firms that have a high adoption level of DFV practices experience a significantly higher rate of technological change compared to the firms that have a low adoption level. The SPDS results (Table 32), which correspond with the findings of paper 3, however, do not indicate significant difference between firms with high modularity and firms with low product modularity in terms of whether these firms experience quick technology shifts. Even more, paper 3 shows that firms that have a high degree of platform thinking (also one of the DFV practices), experience a significantly lower degree of technological shifts compared to firms with a low degree of platform thinking. The IMSS data (Table 30) also shows that the subsamples differ in terms of market size, span and concentration, bargaining power of suppliers and customers and competitive rivalry: firms with a high use DFV practices have markets that consists of more market segments and competitors, have customers and suppliers with stronger bargaining power, experience markets that are growing quicker and encounter more competitive rivalry compared to firms that do not use DFV practices to a high degree. The SPDS data, on the other hand, does not reveal a significant difference between the subsamples in terms of how the firms perceive the competitiveness in their respective marketplaces. However, the data does indicate that firms with high product modularity experience a significantly higher demand for product customization. This is the only environmental characteristic in which the difference between the firms has a medium effect, whereas the other effect sizes are small. Both the SPDS and IMSS datasets reveal that there is no significant difference between the subsamples when it comes to demand fluctuations; the SPDS data does not indicate a significant difference in market demand variation and the IMSS data shows no significant difference between the subsamples in terms of the degree to which the firms' demand, manufacturing volume, product mix and supply requirements change and the degree to which the firm or supplier has to carry out modifications (Table 31). The IMSS data also shows there is no difference between the degree to which the subsamples experience entry barriers for new players and the threat for product substitution (Table 31).

The results of a Chi-Square test, visualized in Table 33 indicates that there is a significant, albeit weak, correlation between the industry the firm is part of and the degree to which a firm uses DFV practices ($\chi^2(5) = 14.97$, $p = 0.010$, Cramer's V = 0.136, $p = 0.010$). There are more firms with a high use of DFV practices than expected in industries that manufacture computer, electronic and optical products (ISIC 26), electrical equipment (ISIC 27), or motor vehicles, trailers and semi-trailers (ISIC 29). Conversely, there are more firms with a low use of DFV practices in industries that either manufacture fabricated metal products (ISIC 25) or machinery and equipment not elsewhere classified (ISIC 28).

Table 33 - IMSS industry results

		25	26	27	28	29	30	Total
High DFV	Actual number of firms	88	44	61	65	34	13	305
	Expected number of firms	99.0	36.0	49.3	78.9	28.5	13.3	
	Std. Residual	-1.1	1.3	1.7	-1.6	1.0	-0.1	
Low DFV	Actual number of firms	173	51	69	143	41	22	499
	Expected number of firms	162.0	59.0	80.7	129.1	46.5	21.7	
	Std. Residual	0.9	-1.0	-1.3	1.2	-0.8	0.1	
	Total	261	95	130	208	75	35	804

For firms manufacturing other transport equipment (ISIC 30), there is no substantial difference between the expected and actual number of firms with high/low use of DFV. Figure 6, which shows the average degree to which firms use DFV practices per industry code, supports these findings as the groups of firms classified as ISIC 26, 27 or 29 have a relatively higher use of DFV practices than firms in the other industries.

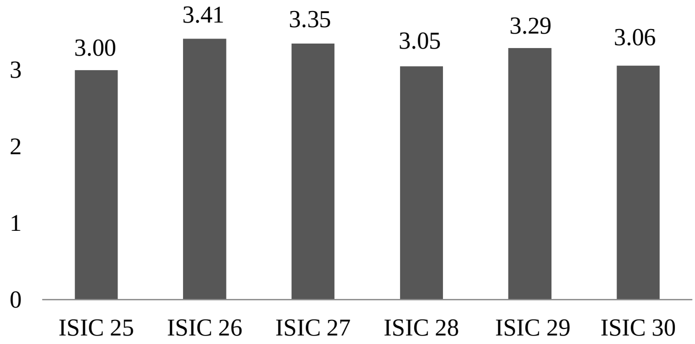

Figure 6 - IMSS DFV mean according to industry

Although the plants with a high use of DFV practices have, on average, 109 employees more compared to plants that have a low use of DFV practices, the difference between the subsamples is not statistically significant (Table 34). Due to outliers in the dataset, this specific t-test comparing SBU size ignores the responses of firms with less than 60 employees and more than 6000 employees, that is, the t-test excludes responses from 10% of the smallest plants and 10% of the largest plants. There is a significant difference in the subsamples in terms of product complexity (Table 35). Firms with a high use of DFV have significantly more parts and materials, a more complex bill of materials, and conduct significantly more steps and operations compared to firms with a lower use of DFV practices. Correspondingly, firms with a high use of DFV practices base a significantly lower portion of their sales on parts and components. Table 36 and Figure 7 illustrate the differences between the subsamples in terms of the percentages of sales based on a) parts and components, b) assembled products and c) services.

Table 34 - IMSS SBU size results

	Number		Mean				Effect
	Low	***High***	Low	***High***	Diff.	Sign.	Size
Size	415	***245***	722	***832***	109	0.245	(0.09)

Table 35 - IMSS product complexity results

	Number		**Mean**				Effect
	Low	***High***	**Low**	***High***	Diff.	Sign.	Size
Parts and BOM	494	***303***	**3.60**	***3.90***	0.29	0.001	(0.25)
Steps and operations	495	***301***	**3.60**	***3.93***	0.33	0.000	(0.33)

Table 36 - IMSS product type results

	Number		Mean				Effect
	Low	***High***	Low	***High***	Diff.	Sign.	Size
Parts and components	467	***289***	32.4 %	***27.4 %***	- 5.0 %	0.041	(0.15)
Assembled products	467	***289***	58.5 %	***62.7 %***	4.2 %	0.095	(0.12)
Services	467	***289***	9.1 %	***9.9 %***	0.8 %	0.455	(0.06)

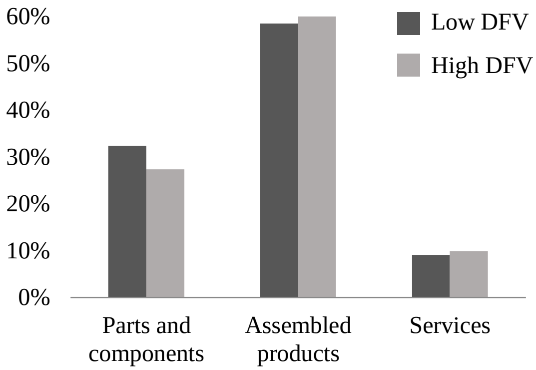

Figure 7 - IMSS product type results

6.2. EFFECTS ON OPERATIONAL PERFORMANCE

To test the effects of product modularity on operational performance, this section uses the results of paper 5 as well as independent t-tests conducted on the IMSS, IMSS-DK and SPDS samples. As part of the mediation analysis conducted to test whether integration mediates the relationship between the use of DFV practices and performance, paper 5 estimates the total effect of DFV practices on the firms' quality, cost and speed, flexibility, service and delivery performance[3]. These simple linear regression analyses show that the use of DFV practices has a positive and significant effect on all performance dimensions included in Table 37.

Table 37 - DFV on performance dimensions (Regression results from paper 5)

	Quality	Cost/Speed	Flexibility	Service	Delivery
Constant	2.899	2.701	2.912	2.795	2.921
b	0.205 [0.157, 0.254]	0.116 [0.076, 0.157]	0.166 [0.121, 0.212]	0.173 [0.123, 0.223]	0.196 [0.143, 0.249]
P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
R^2	0.091	0.044	0.070	0.062	0.069

Independent t-tests based on the IMSS database detail these findings by comparing the performance of firms with high use of DFV practices to those of firms with low use of DFV practices on the underlying performance items (Table 38). These tests indicate that firms with a high use of DFV practices have a significantly higher performance in all items except for manufacturing lead time. The strongest effects are related to introduction ability and customer service quality.

The Swedish SPDS data, however, does not suggest a clear relationship between product modularity and performance, except for the finding that firms with high

[3] The total effect is the effect of the independent variable on the dependent variable without including the mediator.

product modularity also have a larger product variety compared to their major competitors (Table 39). It also seems that product modularity has a small effect on profit margin of the firm, its innovativeness as well as the degree to which it customizes products.

As the Danish subsamples are very small, it is difficult to obtain any significant results based on the Danish data. However, the data does indicate some interesting relationships. First, the subsamples of the IMSS-DK differ little in terms of the time and cost required to develop entirely new products. However, the use of DFV practices might have a large impact on the lead time and costs related to the development of product variants and improvements (Table 40). Finally, the use of DFV seems to decrease the costs and time related to assembly.

Table 38 - IMSS performance results

	Number		Mean		Result		Effect
	Lo	***Hi***	Lo	***Hi***	Diff.	Sign	Size
Conformance quality	468	***295***	3.34	***3.60***	0.26	0.000	(0.37)
Product quality and reliability	468	***295***	3.47	***3.73***	0.25	0.000	(0.34)
Volume flexibility	460	***289***	3.33	***3.56***	0.23	0.000	(0.29)
Mix flexibility	458	***289***	3.32	***3.55***	0.23	0.000	(0.29)
Product customization ability	462	***284***	3.40	***3.58***	0.18	0.005	(0.21)
Introduction ability	464	***277***	3.25	***3.65***	0.39	0.000	(0.44)
Product assistance	451	***285***	3.24	***3.47***	0.23	0.000	(0.30)
Customer service quality	454	***286***	3.21	***3.55***	0.34	0.000	(0.41)
Delivery speed	469	***290***	3.43	***3.60***	0.17	0.004	(0.21)
Delivery reliability	468	***290***	3.40	***3.69***	0.29	0.000	(0.35)
Manufacturing unit costs	443	***276***	2.93	***3.13***	0.21	0.001	(0.27)
Ordering costs	431	***269***	2.94	***3.13***	0.19	0.000	(0.30)
Manufacturing lead time	439	***276***	3.11	***3.21***	0.10	0.101	(0.13)
Procurement lead time	431	***277***	2.99	***3.14***	0.15	0.006	(0.22)

Table 39 - SPDS performance results

	Number		Mean		Result		Effect
	Lo	***Hi***	Lo	***Hi***	Diff.	Sign	Size
Product performance	81	***54***	5.35	***5.37***	0.03	0.883	(0.03)
Quality	80	***53***	5.20	***5.36***	0.16	0.313	(0.17)
Durability	79	***54***	4.81	***4.89***	0.08	0.664	(0.08)
Product development costs	75	***51***	4.12	***4.02***	- 0.10	0.600	(0.10)
Product development time	79	***52***	3.87	***3.98***	0.11	0.570	(0.10)
Profit margin	78	***52***	4.47	***4.77***	0.30	0.177	(0.24)
Product customization	81	***54***	4.91	***5.19***	0.27	0.194	(0.23)
Product variety	80	***53***	4.74	***5.24***	0.60	0.009	(0.47)
Innovativeness	80	***53***	31.16	***37.32***	6.16	0.209	(0.23)

Table 40 - IMSS DK performance results

	Number		Mean		Result		Effect
	Lo	***Hi***	Lo	***Hi***	Diff.	Sign	Size
New product development lead time	21	***9***	3.14	***3.22***	0.08	0.844	(0.08)
Product variant lead time	21	***9***	2.90	***3.56***	0.65	0.051	(0.81)
New product development costs	19	***9***	3.21	***3.22***	0.01	0.964	(0.02)
Product variant development costs	20	***9***	3.10	***3.33***	0.23	0.289	(0.43)
Assembly lead time	22	***9***	3.18	***3.44***	0.26	0.485	(0.28)
Cost of assembly	22	***9***	3.09	***3.56***	0.47	0.079	(0.72)
Manufacturing batch size	20	***9***	3.00	***3.00***	0.00	1.000	(0.00)
Product variety	20	***9***	2.60	***2.56***	- 0.04	0.864	(0.07)
Innovativeness: New products	22	***10***	24.45	***28.80***	4.35	0.567	(0.22)
Innovativeness: Product variants	22	***10***	26.91	***21.00***	- 5.91	0.414	(0.32)
Innovativeness: Existing products	22	***10***	48.64	***50.20***	1.56	0.875	(0.06)

6.3. ORGANIZATIONAL PRACTICES

Three sets of practices related to 1) the product development process, 2) the manufacturing process, and 3) inter-functional and cross-boundary integration, respectively, were found likely to influence the appropriateness of modularity.

6.3.1. PRODUCT DEVELOPMENT

Based on data from the SPDS, paper 3 uses independent t-tests to explore how firms with high product modularity differ from other firms in terms of the way in which they organize their product development work as well as which product development practices they adopted. The results from the tests conducted in paper 3 largely correspond with the results of the t-tests conducted based on the SPDS sample introduced in the previous chapter (Tables 41-42). That is, both sets of tests do not reveal any significant differences between firms with high and low product modularity in terms of the degree to which product development is formalized, co-located, outsourced and conducted by cross-functional teams.

Table 41 - SPDS product development organization results

	Sample		Mean		Result		Effect
	Lo	***Hi***	Lo	***Hi***	Diff.	Sign	Size
Cross-functionality	81	***54***	5.10	***5.43***	0.33	0.224	(0.21)
Co-location	81	***54***	3.67	***3.85***	0.19	0.583	(0.09)
Formality	81	***54***	5.01	***5.28***	0.27	0.378	(0.16)
Outsourcing	77	***50***	12.74	***9.90***	- 2.84	0.361	(0.17)

The SDPS data does, however, suggest a strong relation between the use of platforms and product modularity. That is, the data shows that firms with a high level of product modularity also have a high use of product platforms. Consistent with the findings of paper 3, firms with a high use of product modularity are also found to use QFD and TRL to a significantly higher degree ($p < 0.05$). However, even though paper 3 finds that firms with a high use of product modularity also adopt FMEA ($p = 0.07$) and DFA ($p = 0.07$), the additional t-tests do not find a significant difference between the subsamples' use of these practices.

Table 42 - SPDS product development practices results

	Number		Mean		Result		Effect
	Lo	***Hi***	Lo	***Hi***	Diff.	Sign	Size
FMEA	80	***54***	4.13	***4.65***	0.52	0.122	(0.27)
DFA	80	***53***	3.75	***4.17***	0.42	0.206	(0.22)
QFD	79	***50***	3.10	***3.82***	0.72	0.028	(0.40)
Rapid Prototyping	79	***52***	3.63	***3.81***	0.18	0.622	(0.09)
Agile work	76	***46***	3.21	***3.09***	- 0.12	0.709	(0.07)
Defined gates	80	*52*	4.95	***5.33***	0.38	0.189	(0.24)
TRL	74	*47*	2.84	***3.51***	0.67	0.042	(0.38)
Platforms	81	*54*	3.90	***5.29***	1.39	0.000	(1.01)

In addition to the SPDS, the IMSS-DK is used to explore whether firms with a high use of DFV practices also employ a higher degree of group technology and parallel product development (Table 43). As mentioned, the Danish sample is rather small, so it is not surprising that there is no *significant* difference between the subsamples. However, it does seem that the use of DFV practices might enable the parallel execution of activities in manufacturing and product development, as firms with a high use of DFV practices also have implemented group technology and parallel product development to a higher degree.

Table 43 - IMSS DK action programs results

	Number		Mean		Result		Effect
	Lo	***Hi***	Lo	***Hi***	Diff.	Sign	Size
Group technology	22	***10***	2.64	***3.00***	0.36	0.356	(0.36)
Parallel product development	22	***9***	2.23	***2.89***	0.66	0.115	(0.64)

6.3.2. MANUFACTURING

Independent t-tests based on the IMSS sample show that the degree of DFV adoption is related to the degree to which the firm manufactures to order and assembles to order. Firms with a high use of DFV practices have a significantly larger portion of products that are assembled to order and a significantly lower portion of products that are manufactured to order. However, there is no significant or large difference between the subsamples when it comes to the percentage of products that are designed to order or produced to stock (See Table 44 and Figure 8).

Table 44 - IMSS CODP results

	Number		Mean				Effect
	Low	***High***	Low	***High***	Diff.	Sign.	Size
Designed to order	484	***299***	18.9 %	***19.1 %***	0.2 %	0.921	(0.01)
Manufactured to order	484	***299***	44.1 %	***37.6 %***	- 6.5 %	0.014	(0.18)
Assemble d to order	484	***299***	21.5 %	***27.4 %***	5.9 %	0.012	(0.19)
Produced to stock	484	***299***	15.4 %	***15.8 %***	0.4 %	0.825	(0.02)

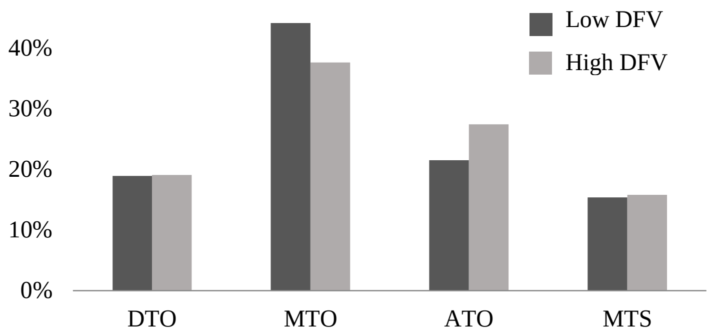

Figure 8 - IMSS CODP results

To explore whether the design of the manufacturing process influences the strength and nature of the DFV-performance relationships, a round of additional t-tests are conducted. Here, the firms are grouped according to their primary CODP, following the same procedure outlined in Paper 4. However, retesting the data from this paper showed that, in paper 4, the firms were not allocated to their right groups due to a mistake in data processing. Therefore, the results presented in Table 45 differ from the results reported in paper 4.

Table 45 indicates that MTO and ATO manufacturers benefit most from implementing DFV practices. However, one should keep in mind that the subsamples for the t-tests conducted for PTS and DTO manufacturers are smaller. MTO manufacturers that use DFV practices have significantly better quality, flexibility, and service performance, are better at introducing new products, and have more reliable deliveries compared to MTO manufacturers that do not use DFV practices to the same extent. The use of DFV practices in ATO environments is associated with other performance benefits. In addition to significantly better quality, ATO manufacturers that use DFV practices also have significantly better delivery, cost and time performance compared to ATO manufacturers with low use of DFV practices. In DTO settings, there is a significant difference in the introduction ability, service quality, procurement lead time and ordering costs between firms with a high use of DFV and those with a low use of DFV. In addition, the use of DFV in these settings is also related to more reliable deliveries, higher quality performance and volume and mix flexibility. However, although the differences between the subsamples in these performance dimensions is rather big (0.25 or more), these differences are not significant. There are no differences between the subsamples' performance for MTO firms. Again, though, there are quite large differences (0.25 or higher) between the subsamples when it comes to the firms' ability to introduce products, and to provide product assistance and customer service. Interestingly, for PTS manufacturers we find some potentially negative performance effects related to using DFV practices. PTS manufacturers with a high use of DFV practices seem to have longer manufacturing and procurement lead times, and are a little bit worse in terms of delivery performance, compared to firms with no or little use of DFV practices.

Table 45 - IMSS, CODP and performance results

		DTO				MTO				ATO				PTS			
		N	Mean	Diff.	Result	N	Mean	Diff.	Result	N	Mean	Diff.	Result	N	Mean	Diff.	Result
Conformance Quality	Lo	60	3.33	0.30	0.063	175	3.27	0.29	0.001	61	3.31	0.28	0.029	40	3.43	0.09	0.548
	Hi	36	3.64		(0.40)	91	3.56		(0.44)	61	3.59		(0.40)	31	3.52		(0.14)
Product Quality	Lo	61	3.48	0.28	0.098	174	3.44	0.23	0.017	61	3.48	0.31	0.022	40	3.55	0.10	0.589
	Hi	36	3.75		(0.35)	91	3.67		(0.31)	61	3.79		(0.42)	31	3.65		(0.13)
Volume Flexibility	Lo	59	3.22	0.31	0.104	172	3.33	0.25	0.014	61	3.43	0.21	0.112	38	3.21	0.24	0.226
	Hi	36	3.53		(0.35)	88	3.58		(0.32)	61	3.64		(0.29)	29	3.45		(0.31)
Mix Flexibility	Lo	59	3.24	0.33	0.066	171	3.26	0.27	0.010	60	3.53	0.13	0.363	38	3.24	0.20	0.268
	Hi	35	3.57		(0.40)	90	3.53		(0.35)	59	3.66		(0.17)	30	3.43		(0.27)
Customization Ability	Lo	59	3.54	0.12	0.502	172	3.33	0.28	0.009	60	3.53	0.13	0.408	39	3.18	0.14	0.488
	Hi	35	3.66		(0.14)	87	3.61		(0.35)	59	3.66		(0.15)	28	3.32		(0.17)
Introduction Ability	Lo	59	3.20	0.68	0.000	173	3.24	0.36	0.002	60	3.42	0.27	0.107	40	3.03	0.37	0.115
	Hi	35	3.89		(0.81)	89	3.61		(0.40)	60	3.68		(0.30)	28	3.39		(0.39)

(Continued on next page)

Table 45 continued – IMSS, CODP and performance results

		DTO				MTO				ATO				PTS			
		N	Mean	Diff.	Result	N	Mean	Diff.	Result	N	Mean	Diff.	Result	N	Mean	Diff.	Result
Product Assistance	Lo	59	3.24	0.16	0.327	168	3.21	0.29	0.006	58	3.29	0.18	0.142	37	3.00	0.29	0.164
	Hi	35	3.40		(0.21)	90	3.50		(0.38)	59	3.47		(0.27)	28	3.29		(0.36)
Service Quality	Lo	58	3.17	0.40	0.032	170	3.18	0.37	0.000	60	3.28	0.20	0.137	38	3.24	0.26	0.236
	Hi	35	3.57		(0.47)	90	3.56		(0.46)	58	3.48		(0.28)	28	3.50		(0.30)
Delivery Speed	Lo	61	3.26	0.11	0.540	176	3.47	0.05	0.624	60	3.45	0.30	0.049	40	3.50	- 0.10	0.572
	Hi	35	3.37		(0.13)	91	3.52		(0.06)	61	3.75		(0.36)	28	3.39		(0.14)
Delivery Reliability	Lo	60	3.27	0.25	0.190	176	3.44	0.24	0.012	60	3.37	0.38	0.015	39	3.54	- 0.02	0.919
	Hi	35	3.51		(0.28)	91	3.68		(0.33)	60	3.75		(0.45)	29	3.52		(0.03)
Manufacturing Unit Cost	Lo	54	2.91	0.09	0.603	171	2.93	0.17	0.067	55	2.93	0.31	0.038	36	3.03	0.05	0.803
	Hi	34	3.00		(0.11)	88	3.10		(0.24)	56	3.23		(0.40)	26	3.08		(0.06)
Ordering Cost	Lo	54	2.85	0.35	0.030	166	2.93	0.13	0.154	55	2.93	0.22	0.018	34	2.97	0.11	0.498
	Hi	34	3.21		(0.48)	84	3.06		(0.19)	54	3.15		(0.46)	26	3.08		(0.18)
Manufacturing Lead Time	Lo	55	3.04	0.11	0.514	169	3.14	0.02	0.877	55	2.98	0.30	0.042	36	3.28	- 0.20	0.311
	Hi	34	3.15		(0.14)	88	3.16		(0.02)	56	3.29		(0.39)	26	3.08		(0.26)
Procurement Lead Time	Lo	55	2.91	0.39	0.013	167	3.07	0.00	0.965	55	2.91	0.23	0.038	34	3.18	- 0.22	0.143
	Hi	34	3.29		(0.60)	89	3.07		(0.01)	56	3.14		(0.40)	26	2.96		(0.39)

6.3.3. INTEGRATION

The t-tests based on the IMSS sample reported in the previous chapter indicate that firms with a high use of DFV practices have significantly higher levels of internal integration with sales and purchasing and external integration with suppliers and customers, compared to firms with little or no use of DFV practices (Table 46). These findings support paper 5, which reports that the use DFV practices has a positive and significant effect on internal integration (b = 0.322, p < 0.01), supplier integration (b = 0.386, p < 0.01) and customer integration (b = 0.322, p < 0.01) (Table 47). Furthermore, paper 5 finds that these three types of integration partially mediate the relationship between DFV and performance. More precisely, all three types of integration partially mediate the effects of DFV on quality, flexibility, service and delivery performance. The relationship between DFV and cost and speed performance is partially mediated by internal and supplier integration, but not by customer integration.

Table 46 - IMSS integration results

		Number		Mean		Result		Effect
		Lo	***Hi***	Lo	***Hi***	Diff.	Sign	Size
Purchasing	Sharing info	488	***299***	3.37	***3.92***	0.55	0.000	(0.65)
Purchasing	Joint decisions	488	***299***	3.24	***3.89***	0.59	0.000	(0.69)
Sales	Sharing info	486	***297***	3.31	***3.91***	0.58	0.000	(0.61)
Sales	Joint decisions	485	***297***	3.18	***3.76***	0.53	0.000	(0.57)
Suppliers	Sharing info	482	***297***	3.06	***3.60***	0.54	0.000	(0.56)
Suppliers	Collaboration	478	***297***	2.94	***3.58***	0.64	0.000	(0.68)
Suppliers	Joint decisions	478	***297***	2.77	***3.47***	0.70	0.000	(0.72)
Suppliers	System coupling	476	***296***	2.55	***3.25***	0.71	0.000	(0.64)
Customers	Sharing info	471	***295***	2.87	***3.47***	0.60	0.000	(0.58)
Customers	Collaboration	474	***294***	2.83	***3.41***	0.68	0.000	(0.63)
Customers	Joint decisions	471	***293***	2.86	***3.51***	0.66	0.000	(0.61)
Customers	System coupling	470	***291***	2.49	***3.21***	0.72	0.000	(0.61)

Table 47 - DFV and integration (Regression results from paper 5)

	Internal integration	Supplier integration	Customer integration
Constant	2.515	1.891	1.965
b	0.322 [0.259, 0.387]	0.386 [0.325, 0.446]	0.345 [0.273, 0.416]
p	< 0.001	< 0.001	< 0.001
R^2	0.153	0.251	0.134

CHAPTER 7. DISCUSSION

The aim of this chapter is to compare and contrast the findings of the survey research with existing modularity research. The chapter is structured according to the three sub-objectives of the thesis. First, it is discussed if and how contextual factors, including environmental heterogeneity, dynamics, and competitiveness as well as firm size and product complexity, influence the adoption rate of modularity. Afterwards, the found relationships between the use of product modularity and manufacturing and purchasing cost and speed, delivery and flexibility, quality and service, and product development, introduction and innovativeness are analyzed. Then, the findings and theory are used to determine if and how the positioning of the customer order decoupling point influences the performance effects obtained through modularity. The chapter also discusses how modularity influences the organization of tasks in product development and production, the link between modularity and well-known organizational and product design coordination practices, and the relationship between modularity, internal integration, external integration and traditional performance parameters. The chapter is concluded with a discussion of the limitations of the research, including the differences between the questionnaires, and a comment on the assumption of causality.

7.1. ORGANIZATIONAL SETTINGS AND CONTEXTS

Even though there is a limited amount of theory regarding contextual contingencies that influence the appropriateness of modularity, some authors have proposed modularity to be more valuable in certain environmental contexts than in others (e.g. Schilling, 2000; Pil and Cohen, 2006; Kamrad *et al*., 2013; Magnusson and Pasche, 2014). Consolidating the suggestions of these authors, section 4.3 concludes that firms can be expected to benefit the most from implementing modularity in heterogeneous and dynamic environments.

7.1.1. HETEROGENEOUS ENVIRONMENTS

Schilling (2000) suggests that modularity becomes more valuable in contextual settings where there are heterogeneous inputs (diversity of technological options and firm capabilities) and heterogeneous demands (customer heterogeneity). Similarly, Pil and Cohen (2006) propose modularity only to be beneficial in markets where there is large product heterogeneity and where customer preferences and technologies are complex, so that competing firms are able to modularize their products in unique ways.

The results presented in Section 6.1 confirm that modularity and related practices are more likely to be implemented in environments with heterogeneous demands. The IMSS data reveals that firms with a high adoption level of DFV practices have a larger average market span compared to firms with a low adoption level. Similarly, the SPDS data confirms that modularity is typically implemented in environments characterized by a higher demand of product customization. However, as noted in Paper 3, it should be kept in mind that even though modularity supports some degree of product customization, several authors (e.g. Da Silveira, 2001; Magnusson and Pasche, 2014) caution that the practice is less appropriate for firms that seek to create truly personalized solutions.

This research thus confirms that firms active in markets with heterogeneous demands are more inclined to implementing modularity than firms in markets with more homogeneous demands. However, further research is needed to detail the relationship between modularization and demand heterogeneity. That is, research that identifies what degree and types of demand heterogeneity modularity can and cannot support, and addresses the type of contexts in which modularity presents a fruitful strategy for providing customization and product variety, contexts wherein, for instance, different modules are capable of embodying real differences in function, performance, quality and so forth, so that the mixing and matching of modules creates diverse solutions with different functional or performance levels. Moreover, further research is needed to establish whether and, if so, why modularity is more prevalent or useful in environments with heterogeneous inputs, that is, environments where there are multiple technologies that can be incorporated in the product.

7.1.2. DYNAMIC ENVIRONMENTS

Product modularity is often promoted as a way for firms to be able to compete in increasingly unpredictable and dynamic environments (Sanchez, 1996; Pine 1993; Pil and Cohen, 2006). It would allow firms to a) respond quickly to changing customer demands by mixing and matching modules, and b) contain the impact of changes and introduce products more frequently as technological progress can be accomplished by developing and substituting only certain subsets of components while the remainder of the product components in the product architecture can remain intact (Garud and Kumaraswamy, 1995; Sanchez, 1999). As developing a modular product architecture is more costly compared to equivalent interconnected systems (Baldwin and Clark, 1997), the practice is less appropriate for firms in very stable, predictable environments, with little fluctuations in market or supply demands, and where customers and/or the firm do not expect a series of future technological developments (Chung *et al*., 2012). Conversely, firms may not be able to reap the long-term benefits of modularity in highly turbulent and immature industries, where technological change cannot be accommodated by continuously developing only subsets of components.

Interestingly, the analyses in this thesis find a very partial and, then, ambiguous, association between the adoption of product modularity (and other DFV practices) and the rate to which the firm experiences environmental dynamics. The IMSS and SPDS datasets reveal no significant differences between the subsamples when it comes to the degree to which a) a firm experiences variation in demand, b) the firm's own demand, manufacturing volume, product mix, and supply requirements fluctuate, and c) the firm or its suppliers have to carry out modifications to their products. However, the IMSS data does reveal an association between the adoption of DFV practices and the rate of technological change and growth in market size experienced by the firm: firms that have adopted DFV practices to a large extent experience a significantly higher rate of technological change and a higher growth in market size compared to firms that have a low adoption level. The SPDS results, on the other hand, do not substantiate these findings, as the t-test does not reveal a significant difference between firms with high modularity and those with low product modularity in terms of whether these firms experience quick technology shifts. The difference between the SPDS and IMSS findings may be due to fundamental differences between the two surveys. This issue will be treated more extensively in section 7.4.

The IMSS finding that firms with a high use of DFV practices only experience a higher rate of technological change and growth in market size, and no other form of environmental dynamics, contrasts several other reports (e.g. Sanchez, 1996). There are several possible explanations, each requiring further research. First, the relationship between modularity and environmental dynamics may not be linear. The theoretical discussion in section 4.3 concludes that pursuing modularity and related practices is less appropriate in very stable markets and in very turbulent markets – making modularity a more appropriate practice to pursue for firms in the middle of the environmental dynamics spectrum. Another explanation derives from the fact that DFV only represents a subset of ways to cope with environmental dynamics. Many other technologies and practices have been claimed to enable firms to more economically adapt to or cope with fluctuations, including manufacturing technologies (e.g. flexible manufacturing systems), manufacturing-design integration software and techniques (e.g. CAD, CAE, CAM and rapid prototyping), and manufacturing practices (e.g. group technology, cellular production, postponement, lean, JIT or flow manufacturing) (see for instance Sanchez, 1995; Kotha, 1995; Sanchez, 1996; Da Silveira *et al*., 2001; Jacobs *et al*., 2007; Liao *et al*., 2010; Jacobs *et al*., 2011). Thus, one reason behind the lack of a direct relationship between DFV and the degree of environmental dynamics can be that this set of practices in itself is not enough to cope with higher degrees of dynamics. Rather, in order to increase a firm’s capability to cope with environmental dynamics, a combination of DFV and one or more of the aforementioned practices might be needed. Paper 4, for instance, theorizes that it is the combination of product modularity and postponement that enables firms to achieve higher degrees of responsiveness. Further research is needed to explore, detail and test if and how modularity interacts with these technologies and practices to successfully cope with uncertain and dynamic environments. Last but not least, another explanation for the lack of relationship between the adoption of DFV and environmental dynamics is that environmental dynamics (including the rate of technological change) in itself may have little impact on the appropriateness of modularity, but first becomes relevant in combination with other environmental factors. Schilling (2000), for instance, proposes that the speed of technological change can provide the urgency for increasing modularity in heterogeneous environments: “*Where technology advances rapidly, both customers and producers desire flexibility in order to respond to the rapidly changing heterogeneity of inputs and demands*” (Schilling, 2000, p. 326). In other words, she proposes that firms are inclined to adopt modularity in environments with heterogeneous inputs and demands, and are more likely to do so in environments with high-speed technological change.

7.1.3. ENVIRONMENTAL COMPETITIVENESS

Schilling (2000) and Fine (1998) proposes that the likelihood of a system's migration towards higher or lower modularity to be dependent on the competitive intensity of its environment; it may lead the firm to adopt modularity in order to differentiate itself and reduce costs at the same time. Similarly, Kamrad *et al*. (2013) conclude that the percentage gain from modularity is higher in contexts with competitive intensity.

The SPDS data do not suggest a difference between firms with a high degree of modularity and those with a low degree of modularity when it comes to the price pressures and competitiveness experienced by the firm. The IMSS data does reveal small, yet significant differences – that is, the dataset indicates that firms with a higher adoption level of DFV practices experience a higher level of market concentration and competitive rivalry and are subject to higher degrees of customer and supplier bargaining power than firms with a lower adoption of DFV practices. The two subsamples of firms in the IMSS, however, do not differ in the degree to which they experience threat of product substitution or market entry. These findings might be explained by the fact that firms facing higher levels of competitive rivalry and customers with stronger bargaining power, are more willing to invest in practices such as modularity in order to differentiate themselves from and/or compete fiercer with their competitors.

While competitive rivalry, market concentration and customer bargaining power may have some effect on the adoption of modularity, the reverse may be true for supplier bargaining power. Observations from the automotive and consumer electronics industries, which have been major sources of empirical evidence for modularity research and are both relatively competitive industries, show that modularity might strengthen the bargaining power of suppliers. In particular, by standardizing components and interfaces, firms, unintentionally or perhaps not, create the possibility for competitors and suppliers to relatively easily imitate the overall product design.

Overall, the findings suggest that the competitiveness of a firm's environment has a weak, if any, and, then, insignificant association with the adoption of DFV. If the data indicate some level of association, the direction of the relationship may differ. Each of these explanations provided for this is tentative, though, and needs further research.

7.1.4. FIRM CHARACTERISTICS

As mentioned before, the automotive and consumer electronics industries have been great sources of inspiration behind modularity theory. The findings of the IMSS verify that modularity prevails in these types of industries: modularity (and related practices) have been implemented to a higher degree in industries that manufacture computer, electronic and optical products (ISIC 26), manufacture electrical equipment (ISIC 27), or manufacture motor vehicles, trailers and semi-trailers (ISIC

29), whereas firms fabricating metal products (ISIC 25) or manufacturing machinery and equipment not elsewhere classified (ISIC 28) implement the practices to a lower degree. Even though larger firms might be more capable of investing the resources needed to pursue modularity, and benefit more from increased component standardization due to larger manufacturing volumes, the IMSS data does not find a difference between the size of firms that have adopted DFV practices to a high degree, and those with a low adoption level.

The IMSS data also confirms that modularity is used more extensively by firms that have a higher product complexity, that is, firms that have a high adoption rate of modularity (and related practices) have products with more parts and materials, more complex Bills of Materials, which require more steps and operations compared to firms that have a low adoption of DFV practices. These results are not surprising. As noted in Paper 1, product modularity is often promoted as a method for complexity reduction, enabling the firm to organize complex products into simpler modules that can be managed independently (Baldwin & Clark, 1997; Sanchez & Mahoney, 1996; Ethiraj *et al*., 2008).

7.1.5. SUMMARY - ORGANIZATIONAL SETTINGS AND CONTEXTS

It is probably a combination of environmental factors that influences the appropriateness of modularity – no single factor in itself can dictate whether modularity is the best practice to pursue in a given contextual setting. The findings indicate that firms are more inclined to pursue modularity when they have higher product complexity and experience customer heterogeneity (increased demand for product customization and larger market spans), higher rates of technological change and growth in market size, and competitive rivalry (higher market concentration, competitive rivalry, higher customer bargaining power). Whether the implementation of modularity is a result of or a contributing factor to increased supplier bargaining power still remains open to debate, though. Among this multitude of factors, the adoption rate of modularity seems to be most influenced by the rate of technological change experienced by the firm and the market demand for product customization.

The general modular systems theory put forward by Schilling (2000) distinguishes between factors that pressure systems to migrate to and from increasing modularity and factors that create urgency, i.e. factors that dictate whether and to what degree the firm responds to these environmental pressures. A similar theory can be proposed based on the findings in this thesis, i.e. where the rate of technological change and market demands for customization are likely to be primary drivers behind the adoption of modularity, and the degree to which the firm experiences competitive rivalry and growth in market size are forces that create the urgency to do so. Illustrating these propositions, Figure 9 sketches a venue for further research.

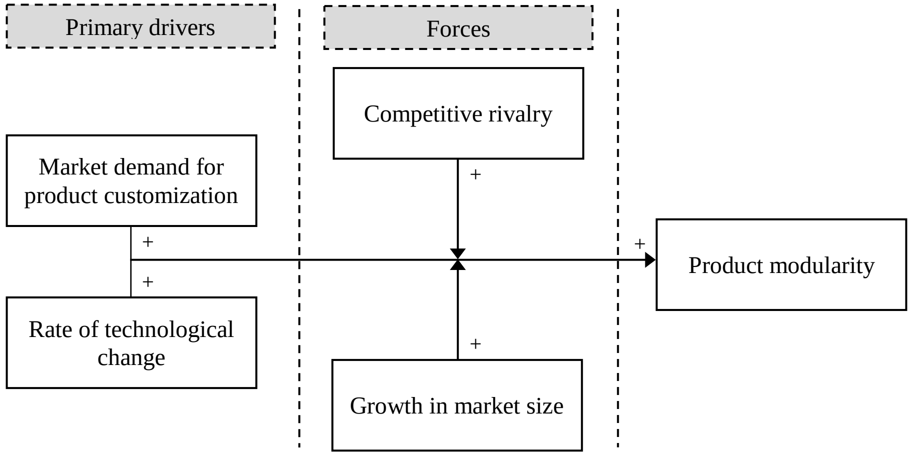

Figure 9 - Primary drivers and forces pressuring firms towards higher modularity

7.2. EFFECTS ON OPERATIONAL PERFORMANCE

Although some authors warn about treating modularity as a panacea (Arnheiter and Harren, 2006; Magnusson and Pasche, 2014), theory generally proposes modularity to have a positive effect on operational performance. Regression analyses performed on the IMSS data confirm this and show that the use of DFV practices is positively associated with quality, cost/speed, flexibility, and delivery performance. In order to discuss how product modularity influences specific operational performance areas, this section delineates between the effects of modularity on 1) manufacturing and purchasing cost and speed, 2) delivery and flexibility, 3) quality and service, and 4) product development, introduction and innovativeness.

7.2.1. MANUFACTURING AND PURCHASING COST AND SPEED

There is a broad consensus in theory that modularity reduces manufacturing and purchasing costs and lead times. The increased levels of component standardization that result from implementing modularity, allow for higher volume, more efficient and faster manufacturing, and low-cost bulk purchasing of standard components (Ulrich and Tung, 1991; Erixon, 1996). Learning curve effects that result from having the same underlying pool of standardized components over extended periods of time will enhance these positive performance effects (Jacobs *et al*., 2007). Existing survey research verifies that product modularity has a positive effects on both cost and cycle time performance (Jacobs *et al*., 2007). The IMSS-DK results, although not significant, indicate DFV practices can play a role in reducing the costs of assembly. Moreover, the results from the IMSS verify that firms with a relatively high degree DFV also have lower manufacturing and ordering costs, as well as shorter procurement lead times compared to firms with a lower degree of DFV. The same dataset, however, does not reveal a significant difference between the subsamples' manufacturing lead time. This is not so surprising. Modularity is a product design characteristic. Manufacturing lead time depends on work content, batch size and layout. The work content of modular designs may be lower but also higher than that of integral designs: integral designs are likely to consist of fewer components that may, however, be more difficult to produce. Further, modularity enables the manufacturer to process components using larger batch sizes, which results in lower total setup times, but also increases work-in-progress. Especially in a functional layout, non-value adding time (work-in-progress) is a major part of lead time. Some authors report that as little as 2-5% of lead time is actually value-adding time in such a manufacturing context. Thus, these aspects related to the manufacturing, rather than the design, of a product are likely to have much greater effect on manufacturing lead time than the modularity of the product. In addition, it is worth noting that Jacobs *et al*. (2007) report effects on cycle time, which is a construct comprised of procurement lead time, manufacturing lead time and delivery speed. One can only speculate about the results these authors would have found if they had studied the effects of modularity on these three time items separately.

7.2.2. QUALITY AND SERVICE

Based on a discussion of the impact of product modularity on eight attributes of quality, Arnheiter and Harren (2006) conclude that modularity can impact quality both positively and negatively. The authors conclude that modularity has the potential to influence the durability and reliability of the resulting products positively, affect the perceived quality and performance of the product negatively, whereas modularity might have both a negative and positive impact on the serviceability of the resulting product portfolio. Component separability resulting from increased modularity enables independent module development and testing, and allows for less costly component replacement and upgrades (Arnheiter and Harren, 2006; Ulrich and Tung, 1991) as well. Furthermore, the learning curve effects that result from increased component standardization can, in the long run, positively impact conformance quality and reliability (Sanchez, 1999). As first noted by Ulrich and Tung (1991), modularity requires the design of generic components, i.e. modules, to be used in multiple products. Therefore, modularity may not optimize the performance of resulting end-products, as these product could likely achieve (even) better functionality through specific components (Arnheiter and Harren, 2006; Schilling, 2000). The overuse of component standardization might also decrease perceived quality, in the sense that it can jeopardize product differentiation (Pasche and Sköld, 2012). The effects of modularity on customer service quality and product assistance and support are less straightforward. On the one hand, the product separability mentioned before allows for quick and easy replacement of modules and, thus, increased speed of aftersales service. On the other hand, modularity may make it necessary to remove an entire module when only one sub-component is faulty (Arnheiter and Harren, 2006).

The IMSS results indicate that firms that employ product DFV to a higher degree also perform better in the areas of conformance quality, product quality and reliability, customer service quality, and product assistance and support. However, the results of the SPDS do not indicate that firms with high levels of product modularity have higher levels of product performance, quality and durability. Existing research confirms the positive relation between modularity and service performance (Lau *et al*., 2007a; 2007b; 2009; Droge *et al*., 2012). However, when it comes to quality performance, the results are less straightforward. While Jacobs *et al*., (2007) and Salvador and Villena (2013) find a positive relation between modularity and quality, Lau *et al*. (2007; 2009) do not. The contradictions between the IMSS and SPDS, and between the findings reported in the literature, need further investigation.

7.2.3. DELIVERY AND FLEXIBILITY

One of the main arguments used to advocate modularity is that it enables firms to mix and match modules to provide product customization and product variety at no sacrifice to volume or cost (Starr, 1965; Sanchez, 1996; Sanchez, 1999). It allows firms to employ late point differentiation, where standard components can be manufactured to stock and combined with variable components on the basis of customer orders (Ulrich and Tung, 1991; Ulrich, 1995; Sanchez, 1995; Sanchez, 1999). This in turn increases the firm's flexibility (including mix and volume flexibility) and delivery speed and reliability (Sanchez, 1995). The IMSS data supports these propositions: firms with high use of DFV practices are found to have higher levels of volume flexibility, mix flexibility, product customization ability, delivery speed, and delivery reliability compared to firms that use the practices to a lower degree. The SPDS also provides evidence that firms that have adopted modularity have significantly higher product variety than the other firms. Even though the difference is not significant, the SPDS also indicate that firms with modularity also have higher degree of product customization. These results fall in line with other survey research results. Except for Lau *et al*., (2009) who do not find a significant relationship between product modularity and delivery, other groups of researchers have found a positive association between product modularity and delivery performance (Droge *et al*., 2012), flexibility (Jacobs *et al*. 2007; Lau *et al*., 2007a; 2007b; 2009), and model variety (Worren *et al*. 2002), respectively.

7.2.4. PRODUCT DEVELOPMENT, INTRODUCTION AND INNOVATIVENESS

In theory, the simplification and standardization of interfaces allows for module-level parallel development activities, allowing for more cost efficient, speedier and more frequent product introduction (Ulrich, 1995; Erixon, 1996; Sanchez, 1996). Survey research tends to agree that the effects of product modularity on product development are positive. In particular, researchers have found modularity to affect NPD time performance (Danese and Filippini, 2010; 2013), new product development (Parente *et al*., 2011), product innovativeness (Lau *et al*. 2009; 2011) and radical innovation (Hao *et al*., 2015) positively. However, this is not reflected in the results of the SPDS, where there is no significant difference in the product development costs and speed and the innovativeness of the two subsamples. The IMSS, however, tells another tale. Here, firms with a greater adoption rate of DFV assess themselves to have better introduction abilities compared to the other firms with low degrees of DFV. Even though the results from the IMSS-DK are not significant, they indicate that adopting DFV does not influence the time and costs associated with developing *new products,* but that the practices do reduce the time firms need for developing *product variants.*

7.2.5. SUMMARY - EFFECTS ON OPERATIONAL PERFORMANCE

Based on this and other survey research, there is pervasive evidence that modularity positively influences cost, flexibility, delivery, and service performance. When it comes to quality and product development performance, however, the two surveys – SPDS and IMSS – do not agree. The reasons for these discrepancies will be discussed in section 7.4. Figure 10 summarizes the findings discussed above, outlining the product characteristics and product effects of modularity as well as indicating the theoretical mechanisms by which modularity influence performance. In addition, Figure 10 illustrates the performance effects that have been found to be significant and positive (boxes with a straight line) and the performance effects that are not significant, but where the research has provided a strong indication of a positive effect (boxes with dotted lines). However, more empirical research is needed to detail the relationship between product modularity and 1) quality performance, 2) time performance, 3) product development performance and 4) innovativeness. Research could attempt to pursue a more fine-grained operationalization of the latter performance areas. For instance, by delineating between manufacturing, assembly and delivery time performance, and between new product development, product variant and product improvement cost and time performance, researchers could pinpoint what underlying performance dimensions modularity does and does not affect. Researchers could also put more effort into exploring how modularity affects innovativeness. Like in the IMSS-DK survey, researchers could delineate between the percentage of sales based on a) new products launched within the last three years, b) product variants and product improvements launched within the last three years, and c) existing products launched more than three years ago. Fine-grained operationalization is even more important in the area of quality, which encompasses a wide range of sub-dimensions. Surveys exploring product modularity, and this survey is no exception, tend not to detail these sub-dimensions, even though items such as “product quality”, “quality” and “product performance” can be interpreted in widely difference ways.

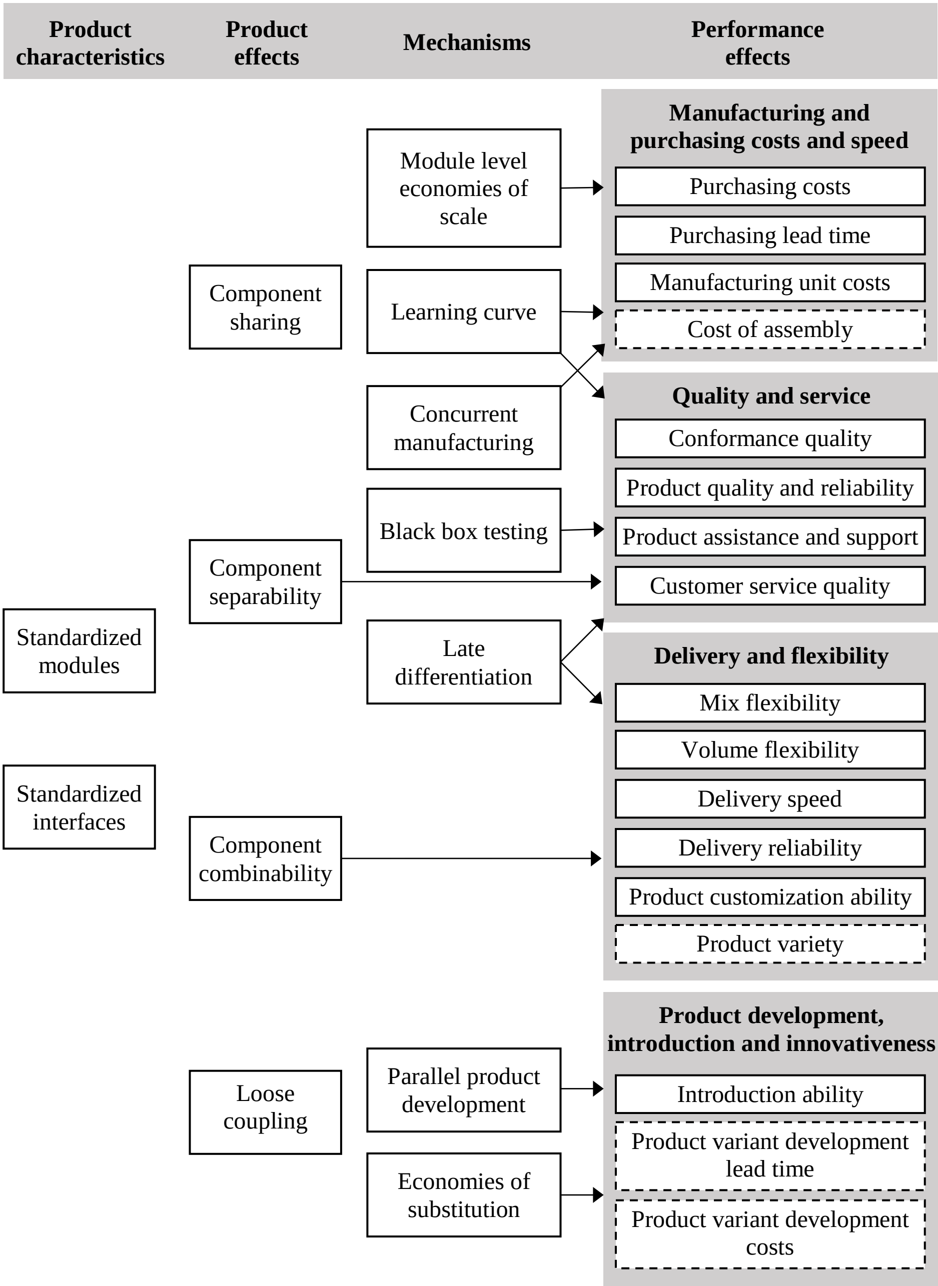

Figure 10 – Link between product characteristics and performance effects of modularity

7.3. ORGANIZATIONAL PRACTICES

7.3.1. MANUFACTURING PROCESSES AND PRACTICES

As mentioned in section 4.5, "*most theorists who argue for modularity and its ability to overcome the variety-performance trade-offs, implicitly assume that it is implemented in a firm employing small or large batch manufacturing. In such a setting, modularity allows the firm to divide between a) the cost-efficient manufacturing and sub-assembly of standardized modular components and b) the final assembly process, which mixes-and-matches these components once customer requirements are known*". The IMSS data confirms that firms that use modularity (and related practices) to a higher degree are more inclined to assemble-to-order, and less inclined to use manufacture-to-order. In other words, the data shows that modularity allows "*the firm to position the CODP midstream and postpone the final manufacturing and assembly tasks by separating the forecast-driven mass-production of semi-finished goods and modules from providing customized end-products based on specific customer orders*" (Paper 4, p. A58).

Paper 4 hypothesizes that the position of CODP influences the performance effects that can be achieved by the implementation of DFV practices. In particular, the paper states that "*there is no reason to believe that the learning curve effects from producing and assembling the same pool of standardized components over a prolonged period of time would depend on the firm's CODP. Other performance effects, however, may be more dependent on the positioning of the CODP. The mid-stream positioning of the CODP combined with the use of DFV practices enables firms to efficiently produce and deliver customized end-products and, thus, balance the ability to provide increased customer responsiveness with cost efficiency (Van Hoek, 2001). However, if a firm positions its CODP more downstream (in the form of make-to-stock), it is less likely to be able to benefit from DFV practices to achieve combinatorial variety, which means that it foregoes the benefits of enhanced customer responsiveness. If, in contrast, a firm positions its CODP upstream (in the form of engineer-to-order), it is less equipped to use the increased component commonality resulting from the use of DFV practices to achieve economies of scale*. (Paper 4, p. A58-59)".

The IMSS results confirm this hypothesis, and indicate that the performance effects that can be achieved from implementing DFV are highly dependent on the positioning of the CODP. Firms with a midstream positioning of their CODP benefit the most from implementing DFV. Both MTO and ATO manufacturers with high use of DFV have greater conformance and product quality as well as delivery reliability performance. In addition, MTO manufacturers gain stronger customer/ responsiveness (i.e. volume and mix flexibility, product customization ability, product assistance and customer service quality) effects from employing DFV, whereas ATO manufacturers benefit most in processing related performance areas (delivery speed, manufacturing unit costs, ordering costs, manufacturing lead time, procurement lead time). Albeit to a lesser extent, DTO manufacturers also benefit from implementing DFV. This is a very interesting observation, as most research in product modularity focuses on products where the underlying pool of components have already been designed prior to the customer order entry point. That is, most research take point of departure in the premise that product modularity allows for the mixing and matching of standardized and, thus, existing components, according to individual customer needs. However, Ulrich and Tung (1991) argue that modularity also encompasses the instance where a make-to-order or custom component is matched with an otherwise standard product. In this instance, firms can stock the bulk of standardized components, and focus their efforts on the customized components (Ulrich and Tung, 1991). This could explain why DTO manufacturers with high use of DFV perform significantly better in terms of introduction ability, service quality, ordering costs and procurement lead time. It seems that PTS firms benefit the least from implementing DFV: there are no significant performance differences between PTS manufacturers with a high DFV adoption level and those with a low adoption level.

The results indicate that the extent to and way in which firms can benefit from modularity (and related practices) does depend on their CODP positioning, a conclusion for which little empirical evidence was produced so far. However, the results do not provide much explanation yet, and further in-depth investigation is needed to develop (tentative) explanations for these findings. Research could explore differences between how DTO, MTO and ATO manufacturers adopt modularity – and under what conditions modularity is an appropriate solution for these manufacturers. Research could especially benefit from a more in-depth exploration of the use of modularity in design- or engineer-to-order environments, which is an area that has received little attention so far.

7.3.2. THE MIRRORING HYPOTHESIS

A central theme in the modularity literature is the mirroring hypothesis, which proposes that the module independency resulting from the increase in interface standardization will reflect itself in the organization of product development tasks (Sanchez, 1995; Sanchez and Mahoney 1996, Sanchez, 1996; Baldwin and Clark, 1997; Sanchez, 2000). Even though the results are not significant, the IMSS-DK does indicate that firms that have adopted DFV also conduct parallel product development. That is, these firms 'divide their design tasks, so that autonomous teams design, develop and experiment with independent components in parallel' (parallel development item in the IMSS-DK survey). Conversely, the SPDS does not detect a significant relationship between the use of product modularity and the outsourcing of product development tasks, and even more so, indicates that firms with high modularity outsource their product development work less compared to firms with a low use of product modularity. These inconclusive results are, however, not surprising. Even though there is an abundance of literature that suggests that modularity leads to, or should be combined with, an externalization of innovation and product development efforts, where firms will partake in a loosely coordinated network with suppliers or competitors in their efforts to create new products (Langlois and Robertson, 1992; Garud and Kumaraswamy, 1995; Sanchez, 1996; Sanchez and Mahoney, 1996; Baldwin and Clark, 1997; Chesbrough and Kusunoki, 2001), other authors do not detect such a relationship. Brusoni and Prencipe (2001) and Ernst (2005), for instance, contest that firms or networks developing modular products need more than standardized interfaces within the product design to achieve intra- and inter-organizational coordination. These findings are backed up by various authors (e.g. Brusoni and Prencipe, 2001; Sosa *et al*., 2004; Genba *et al*., 2005; Ro *et al*., 2007), who observe that innovation and engineering efforts in the car and aircraft engine industries still are very much located at the original equipment manufacturer.

These inconclusive results suggest that more empirically based research is needed to establish how modularity influences the organization of development tasks, work similar to that of Sosa *et al*. (2004), who study the misalignment between product architecture and organizational structure in the development of a large commercial aircraft engine. This research needs to dig beneath the surface of the premise that "products design organizations" (Sanchez, 2000), and empirically explore, amongst others:

- How does modularity influence the organization of different types of product development processes (such as the development of entirely new products, the development of product variants, the development of product improvements)?
- When and how modularity leads to successful "modular" product creation processes, by detailing if, when and how standardized design interfaces provide a strong enough coordination mechanisms for independent design activities. This might also include a discussion of the assumed link between product design and organizational design, answering, for instance, the question whether an integral product can be developed by a modular product development organization (Campagnolo and Camuffo, 2010).
- The relationship between product modularity and the outsourcing of development activities: if such a relationship exists, which external and internal factors influence the alignment between product modularity and boundary choices and what types of activities are moved out of the firm boundaries as a result of increasing modularization (Campagnolo and Camuffo, 2010)?

Similar work could be done in exploring the effects of product modularity on the organization of tasks in manufacturing. Even though the IMSS-DK does not indicate any significant differences between the subsamples in terms of their use of group technology, there is an abundant amount of research that assumes or tests a link between the use of product modularity and the organization of manufacturing tasks (e.g. Ulrich, 1995). In survey research, researchers often test the effects of "process modularity" alongside product modularity. Defined by Droge *et al*. (2012) to be "*the incorporation of adaptable and reconfigurable tooling and routings into production operations to effectively meet heterogeneous demand*", Jacobs *et al*. (2011) and Droge *et al*. (2012) measure process modularity as the use of cellular manufacturing, group technology, flexible manufacturing systems and general-purpose equipment. Tu *et al*. (2004), Liao *et al*. (2010) and Thatte (2013), however, interpret the construct differently and base their operationalization on Feitzinger and Lee's (1997) three principles, which are 1) process standardization, 2) process resequencing, and 3) process postponement. From the above five groups of survey researchers who address process modularity, Jacobs *et al*. (2011) are the only ones to test and verify a positive link between product and process modularity. More work could therefore be done to theorize and test the impact of product modularity on the organization of production tasks, including the link between flexible manufacturing systems, general purpose equipment, group technology and cellular manufacturing. This research could take its starting point in the proposition formulated in section 4.5: "*Whereas the former two practices might enhance the performance effects of modularity, product modularity is said to enable the adoption of the latter two practices. Thus, while flexible manufacturing systems and general purpose equipment could play an important role as moderators of the modularity-performance relationship, group technology and cellular manufacturing are potentially mediators in the modularity-performance relationship*".

7.3.3. PRODUCT DEVELOPMENT ORGANIZATION

Existing theory, especially survey research, is interested in the relationship between modularity and cross-functional integration. More specifically, plenty of survey research examines the relationship between product modularity and internal integration, operationalized as the degree of coordination between design and other internal functions (Lau *et al*., 2007b; Lau *et al*., 2009; Lau *et al*., 2010; Ahmad *et al*., 2010; Danese and Filippini, 2010; Zhang *et al*., 2014). These authors find internal integration to be a requirement for successful modularity efforts (Lau *et al*., 2007b; Lau *et al*., 2010; Zhang *et al*., 2014), product modularity and internal integration to interact to improve performance (Lau *et al*., 2009; Danese and Filippini, 2010), or modularity to improve internal integration, which in turn improves performance (Ahmad *et al*., 2010). The nature of the relationship between the use of product modularity, integration, and performance will be discussed in section 7.3.5. Regardless of the specific nature of the relationship between internal integration and product modularity, most researchers find evidence for a significant relationship between product modularity and internal integration (Lau *et al*., 2007b; Lau *et al*., 2010; Ahmad *et al*., 2010; Zhang *et al*., 2014). Given these results, it is natural to also expect a positive link between the use of product modularity and the use of cross-functional teams. Even though the results are not significant, the SPDS data suggests that firms with high modularity conduct a larger portion of their product development work through cross-functional teams. Also the IMSS finds a positive relationship between product modularity and internal integration, further elaborated on in the section 7.3.5.

Except for this research into the link between the use of product modularity and cross-functional integration, few modularity studies explicitly discuss the link between the use of modularity and other well-known organizational coordination mechanisms used during product development, such as standardization (through e.g. stage-gate and performance management), mutual adjustment (through e.g. scrum), job rotation, and co-location. So, even though modularity research has plenty of suggestions in regards to how modularity influences the division of work, no guidelines are provided for how to achieve the best coordination of this subsequent division of work. Sanchez (2000), however, does recognize the importance of new performance measures to manage modular product development as well as a more formal product development process with well-documented component interfaces. In addition, the product platform literature, an adjacent field to modularity, emphasizes that a disciplined approach to the development of product families is crucial for a firm's long-term success, and provides several guidelines for how to do so (Wheelwright and Clark, 1992; Meyer and Utterback, 1993; Meyer and Lehnerd, 1997; Robertson and Ulrich, 1998). So, even though the results represented in this thesis show no significant differences between the way firms with low and high adoption levels of modularity organize product development, including the extent to which they use co-location of project management, formal product development processes with defined stages and/or gates (e.g. stage-gate) and agile work (e.g. scrum), further research is needed; research that elaborates how existing coordination mechanisms and practices can be adjusted and used to ensure successful modular product development. This research could, for instance, detail how performance management, project management, planning and control systems, and incentive systems are, can or should be adjusted in order to coordinate modular product creation processes.

7.3.4. COMPLEMENTARY PRODUCT DEVELOPMENT PRACTICES

In addition to testing whether firms with low and high adoption levels of modularity differ in the degree to which they use organizational mechanisms to coordinate product development, the SPDS data is also used to see whether the subsamples differ in the degree to which they adopted certain design mechanisms that facilitate cross-functional integration. The results indicate that firms that adopted product modularity to a higher degree, also adopted quality function deployment, TRL classification and product platforms to a significantly higher degree, while there is no significant difference between the subsamples in terms of the adoption rate of failure mode and effects analysis, design for assembly, and rapid prototyping (stereolithography, selective laser sintering).

The strong association between the use of product platforms and product modularity is not unexpected. Not only are the two practices very similar, as they both emphasize standardization of components and interfaces and both rely on economies of substitution, the use of the practices can be complimentary in certain settings. First, as mentioned in section 4.6. "*Modularization efforts help determine which standardized components and modules should form the basis for future product family variants, and also creates the standardized interfaces that can help decoupling these standardized, common platform components and modules from the variable, peripheral components (Baldwin and Woodard, 2009)*" (p. A50). Second, building the stable core set of components that are to remain unchanged across product models and generations based on modular principles allows the platform to vary in itself, and thus enables an even stronger basis for leveraging a large number of designs.

The use of quality function deployment combined with product modularity is no surprise, either. Quality function deployment is proposed to be one of the steps to undertake in developing modular products using Modular Function Deployment – a popular modularization technique proposed by Erixon (1996), where modularity requirements as well as design requirements are derived from customer/market needs. The use of TRL classification combined with product modularity, however, is a topic less treated in existing literature, and is, thus, an interesting area for further research. As mentioned in paper 3, the use of TRL classification for firms with high degrees of modularity makes intuitive sense, since "*these firms have to respond to or lead technological change by integrating new technology into an already existing product structure and architecture (Sanchez, 1995). Without having an assessment of the risks and manufacturing readiness of the new technology and an approximation of the time and costs it takes to fully mature this technology (Britt et al., 2008), the firm can risk a disruption in their platform plan or risk including immature technology into core platform or product architecture*" (Paper 3, p. A44).

Surprisingly, firms with high degrees of product modularity are not found to have increased use of design for assembly[4]. Other authors have found a relationship between the use of product modularity and other design integration mechanisms – including design for manufacturing (Jacobs *et al*., 2007), which is a practice that is often implemented together with design for assembly. One explanation for this apparent inconsistency is, however, that the pool of firms in the SPDS may have chosen to implement either product modularity or design for assembly in their quest for minimizing the costs of product variety. Anyway, more research is needed to establish whether product modularity and design for assembly are complementary.

7.3.5. PRODUCT MODULARITY, INTEGRATION AND PERFORMANCE

Paper 5 explores the role of internal, supplier and customer integration in the relationship between DFV and performance based on IMSS data.

Even though researchers agree that internal cross-departmental and external cross-boundary integration are important factors in the relationship between DFV and performance, they do not agree on the nature of this role. Paper 5 summarizes the inconsistencies in existing survey research: *"Various research models have been proposed. Some studies model integration as a moderator on the DFV-performance relationship, other studies regard integration as a (partial) mediator in that relationship, and yet other studies investigate integration as an antecedent of DFV"* (Paper 5, p. A69).

The role of integration in the implementation and use of product modularity depends on the maturity of the modularity effort. During the system level design of a modular product portfolio, literature emphasizes that functional units such as design, manufacturing, marketing and purchasing, need to coordinate in order to design modular components that can be designed and manufactured independently as well as meet diverse customer requirements (Starr, 1965; Lau *et al*., 2009; Ahmad *et al*., 2010). In order to be able to meet these customer requirements, authors even argue that there is a need for explicit co-development with customers in order to obtain

[4] In the IMSS, this practice is pooled into the same construct as product modularity, as both practices have the overall ambition to minimize internal complexity by simplifying the product design, standardizing components, interfaces, and assemblies, and also promoting the creation of interchangeable modules (see paper 5).

information about market and customer preferences (Lau *et al*., 2007b). In a similar vein, authors also argue that product co-development with suppliers is crucial in the initial phases of modularization in order to, amongst other, develop a modular supply system (Danese and Filippini, 2010; 2013), share information on engineering parameters (Lau *et al*., 2007b), and reduce interface constraints (Howard and Squire, 2007). As a result, there is a strong argument in theory for inter-functional and inter-firm integration as a prerequisite for successful modularization efforts.

This thesis argues that, although there is no denying that the successful design of product portfolios requires an understanding of internal and supplier processing capabilities and customer preferences, there is no convincing argument that this requirement is specific to the design of modular products. As Ahmad *et al*. (2010, p. 48) put it *"product design is inherently an interdisciplinary behavior"*. All product development endeavors, not only those that are focused on creating modular products, require inter-functional and cross-boundary integration. However, what does make modular product design different from other design efforts is that it facilitates cross-functional and cross-boundary integration through the standardization of interfaces and the information hiding principle. The creation of rules dictating how the modules are to interact (interface standardization) and the partitioning of information into visible design rules and hidden design information (information hiding) ensures that key information about the individual modules will be codified and externalized, whereas detailed knowledge about the components will remain within the individual design teams. By restricting communication between design entities to key product information embedded in the component interfaces, modularity enables design teams to communicate more clearly, with less effort and more frequently (Jacobs *et al*., 2007; Droge *et al*., 2012; Danese and Filippini, 2013). Therefore, paper 5 concludes that, instead of being an antecedent to, or moderator in, the DFV-performance relationship, integration is more likely to play a role as a mediator in this relationship[5].

The results of mediated regression analysis performed on the IMSS data in paper 5 verify that there is a direct connection between product modularity and internal cross-departmental integration and external integration with customers and suppliers. Further, except for customer integration in the DFV-cost/speed performance relationship (no mediation), all three types of integration mechanisms are found to partially mediate the relationship between DFV and cost/speed, quality, delivery, flexibility and service performance. This indicates that "*in addition to helping manage and mitigate the negative impact of customer demands for product variety on operational performance, DFV practices also provide a mechanism supporting cross-functional and cross-boundary integration, which further enhances the performance effects of DFV*" (paper 5, p. A68). As integration has been widely

[5] Tests, not reported in this thesis, do indeed confirm that integration does not moderate the relationship between DFV and performance: only 1 out of 15 potential relationships between 1) DFV, 2) internal, customer, and supplier integration, and 3) cost/speed, quality, delivery, service and flexibility performance tested positive for moderation, whereas 14 out of the 15 possible relationships tested positive for mediation.

proven to have positive performance effects in itself, firms employing modularity might achieve additional performance effects by actively using the principles of interface standardization and information hiding as mechanisms supporting information sharing and decision making across design entities.

7.4. DIFFERENCES BETWEEN THE SPDS AND IMSS

The discussion indicated some discrepancies between the results of the SPDS and IMSS. As summarized in Table 48, the IMSS found significant differences between its subsamples in certain environmental and performance items, where the SPDS did not reveal such differences in equivalent items. This can be due to a number of reasons, including differences in measurement (item operationalization, wording, scaling) and sample characteristics (sample size, demographics). The differences regarding the degree to which firms experience technological change and competitive rivalry are not easily explained without further insight into the specifics of the firms in the IMSS and SPDS samples, insight that goes beyond the data provided by the two questionnaires. The inconsistencies between the findings of the SPDS and IMSS in the performance items can, however, largely be explained by addressing the most prominent measurement and sample differences between the two surveys.

Table 48 - Differences between the SPDS and IMSS

		IMSS						SPDS			
		N	Mean	Diff.	Result			N	Mean	Diff.	Result
Rate of techn. change	Lo Hi	498 304	3.12 3.47	0.36	0.000 (0.37)	Quick techn. Shifts	Lo Hi	80 54	3.18 3.20	0.03	0.899 (0.02)
Competitive Rivalry	Lo Hi	496 304	3.79 3.95	0.16	0.021 (0.17)	Competitiveness	Lo Hi	80 54	5.55 5.50	-0.05	0.799 (0.04)
Conformance quality	Lo Hi	468 295	3.34 3.60	0.26	0.000 (0.37)	Quality	Lo Hi	80 53	5.20 5.36	0.16	0.313 (0.17)
Product quality and reliability	Lo Hi	458 295	3.47 3.73	0.25	0.000 (0.34)	Durability	Lo Hi	79 54	4.81 4.89	0.08	0.664 (0.08)
						Product performance	Lo Hi	81 54	5.35 5.37	0.03	0.883 (0.03)
Product cust. ability	Lo Hi	462 284	3.40 3.58	0.18	0.005 (0.21)	Product customization	Lo Hi	81 54	4.91 5.19	0.27	0.194 (0.23)

Even though the IMSS and SPDS address similar types of firms, their sample sizes are very different. The IMSS sample used for the reported tests consists of 931 firms from 21 countries, which is more than six times larger than the SPDS sample used, which consisted of Swedish 141 firms. Although the tests conducted on the SPDS and IMSS indicate similar mean differences regarding the subsamples' ability to customize products, the difference in sample size may explain that only the IMSS statistics estimate the differences between high and low adopters to be significant.

The most noticeable measurement difference between the two survey studies is how the independent variable is operationalized. Where the SPDS captures the degree of product modularity implemented by asking the respondents to assess the degree of component separability, loose coupling and component combinability in their main products, the IMSS assesses the degree to which the focal firm has implemented Design for Variety practices, including modularity, but also standardization, platform design, DFM and DFA. While this dissimilarity in operationalization may only explain part of the discrepancies between the SPDS and the IMSS results, it might prove to be most crucial in explaining why the IMSS reveals a significant mean difference between the conformance quality and product quality and reliability performance effects of the subsamples, whereas the SPDS reveals no significant mean difference between the quality, durability and product performance effects of the subsamples. The results imply that it is not the degree of modularity implemented by the firm (as per the SPDS survey) that dictates whether it can achieve higher levels of quality compared to its major competitors, but rather it is one or more of the other DFV practices (as per the IMSS survey) that influence quality performance. As noted in paper 5, DFM and DFA advocate fail-safe manufacturing and assembly, which reduces defects and failure rates (Boothroyd, 1994) and can, thus, be expected to have a direct and positive effect on product quality and reliability as well as conformance quality. So, the IMSS seems to suggest that the difference between its respective subsamples in terms of product quality and reliability results from the degree to which the subsamples have implemented DFA and DFM, but is not influenced by the degree to which the subsamples have implemented modularity. More research comparing as well as delineating the different DFV practices is needed to test this tentative explanation; research similar to that in Paper 3, which is a paper that addresses the contexts in which the combined or separate use of modularization and platform thinking is appropriate, and discusses and tests which product development practices have the potential of complimenting these two DFV practices.

7.5. CROSS-SECTIONAL DATA AND CAUSALITY

The data whereupon the conclusions are based is cross-sectional. It is taken from multiple industries, but at one point of time. This compromises the assumption of causality. In this thesis, the assumption is that the firm’s adoption of modularity causes a subsequent increase in specific operational performance areas and also increases the degree of integration between functions in the firm, and with customers and suppliers. Although these assumptions are strongly founded in existing theory, there is no way of telling whether modularity is the cause of the effects studied, or whether it is the effect itself. That is, even though many researchers argue that modularity increases firm performance, the opposite proposition might also be true – that firms with higher degrees of performance are more inclined to pursue modularity. Firms with higher performance will, arguably, have more resources available to pursue practices such as modularization in their efforts to increase performance even more.

The theory of institutional isomorphism (DiMaggio and Powell, 1983) provides another, slightly different perspective on the relationship between modularity and performance. Seeking to explain homogeneity of organizational forms and practices, this theory proposes three mechanisms by which the process of homogenization occurs, namely coercive, mimetic and normative isomorphism (DiMaggio and Powell, 1983). Especially the latter two of these mechanisms might explain why high-performing firms choose to adopt modularity. Early modularity researchers have been effective in promoting modularity to such a degree that it is now a common practice known to industry, consultants and researchers. Like other practices that have been known to be subjected to isomorphism, descending, for instance, from the Japanese production philosophies, the modularity concept can be adapted to a wide range of firms, and its advantages are relatively easily conveyed. Therefore, it might not even be the rational pursuit of higher performance that drives certain organizations to pursue modularity, but rather, mimetic and even normative isomorphism. The theory of institutional isomorphism also provides a new perspective on the environmental differences between firms with a high, and those with a low, adoption of DFV. Perhaps it is not so much environmental heterogeneity or rate of technological change *per se* that drives the adoption of DFV but, rather, institutional imitation. In other words, firms, especially, if they are in the same (type of) industry, copy each other’s practices, without necessarily considering their “goodness”.

In addition to the problem of causality, the data does not inform the specific timing of the effects, either. Even if we assume that the reported performance effects are indeed a direct or indirect cause of product modularity, little can be said about *when* the firms experienced *what* effects of modularity. What we do know is that firms cannot expect instant performance benefits from implementing modularity. Designing modular systems is more difficult and requires a higher amount of initial development resources and time compared to the design of comparable interconnected systems (Baldwin and Clark, 1997). In addition, shifting from one product structure to another could also require the firm to adapt or discard prior products and adjust existing manufacturing processes. Then, only when the modular system is in place, the firm can reap the long-term benefits of standardization in its manufacturing processes and pursue economics of substitution in its product innovation processes. Reaping the benefits of modularity thus requires time. More research is needed to detail when and how different types of firms can offset the initial costs and time involved in developing modular systems and achieve superior performance by pursuing modularity.

CHAPTER 8. CONCLUSION

Spurred by the overall objective of ascertaining "how modularity influences the performance of manufacturing firms", the PhD process began with an extensive literature review focusing on studies that either a) discuss the implications of product modularity on the manufacturing firm or b) have played a prominent role in influencing the modularity literature. This literature study revealed that the development of modularity research has been greatly motivated by two core assumptions developed during the early attention-seeking and theory development stages, assumptions positing product modularity to:

- Enable or even lead to a higher disintegration of product development and manufacturing tasks within and across firm boundaries.
- Have a positive effect on firm performance.

As visualized in Table 49, both core assumptions are substantiated by an abundance of propositions, which are put forward, based on anecdotal evidence, singular success stories, or prior findings from adjacent research.

Table 49 - Core assumptions in modularity research

Core assumption 1: The disintegration of tasks within and across firm boundaries
Underlying propositions
Mirroring hypothesis - The standardized interfaces in the modular product design will enable individual design entities to conduct product development tasks autonomously and concurrently within firm boundaries (organizational modularity) or across firm boundaries (market modularity).
Supply chain disintegration - The adoption of modularity will not only enable market modularity, but will inevitably result in vertical disintegration of supply chains.
Black box sourcing - Employing modular design principles supports black box sourcing, where suppliers not only produce components, but also design and develop them.
Process modularity - Product modularity allows for late-point differentiation of products and parallel completion of production tasks, where standard components can be manufactured-to-inventory and combined with variable components on the basis of customer orders.
Research status
While observations from the consumer electronics industry verify the link between product and market modularity, these effects are not observed in other industries (including the automotive, chemical engineering and aircraft engine industries). In these industries, supplementary coordination is needed to coordinate product development efforts.
Little empirically-based research addresses the proposed link between product, organizational and process modularity. Jacobs et al. (2011) do find a link between product and process modularity, but operationalize the latter as the use of cellular manufacturing, group technology, flexible manufacturing systems, and general-purpose equipment.

(Continued on next page)

Core assumption 2: Positive performance effects

Underlying propositions

Operational performance/mass customization - Modularity enables the production and sub-assembly of standardized components according to mass production principles, allowing for traditional economies of scale advantages on component (rather than product) level. It also allows for the delay of final assembly processes until customer requirements are known, supporting the combination of cost-efficient production with increased product flexibility (mix, change-over, and modification flexibility) and delivery (reliability and speed) performance. In addition to traditional economies of scale benefits, modularity also supports learning curve effects, resulting in the continuous improvement of speed, cost and quality performance. After product sales, the detachable modules support easier maintenance and superior service performance, enabling the company to provide upgrades, add-ons, and refills.

New product development performance - The standardized interfaces in a modular product architecture allow for concurrent, autonomous product development, reduce the amount of cycling in the development process and therefore leads to quicker, less costly and more frequent product introductions.

Research status

Survey research supports the conclusion that modularity improves overall operational performance and supports mass customization. There are, however, conflicting results regarding the effects of modularity on specific areas, including cost and quality performance. Guo and Gershenson (2007) and Arnheiter and Harren (2006) further highlight potential positive *and* negative effects of modularity on cost and quality performance, respectively.

Although survey research indicates that modularity has a positive effect on overall product development performance, little is known about the long-term effects of modularity on innovation performance. Modelling research indicates that nearly modular structures present the best trade-off between innovation benefits and imitation deterrence.

Survey research has so far focused on one practice – integration - in its attempt to explore *how* modularity influences performance. However, the researchers do not agree whether integration is a predecessor to successful modularization or instead, a mediator or moderator in the relationship between modularity and performance.

Currently, modularity theory is in a phase where these overly enthusiastic propositions are put under scrutiny using empirical evidence. After the turn of the century, researchers began using case research, modeling and survey research to test whether and how product modularity, amongst others, leads to or enables organizational and market modularity, is related to cross-functional and cross-boundary integration, influences the innovation potential of the firm and its product development performance, and affects operational performance.

The thesis predominantly addresses the latter research stream; focusing not only on *what* operational performance effects firms achieve by implementing modularity, but also on *how* product modularity influences the manufacturing firm and its performance. The main objective of this research is to determine:

How organizational practices and context affect the association between product modularity and the performance of manufacturing firm.

Existing conceptual and empirical research mainly address the *direct* effects of modularity and performance, proposing or testing the potential performance effects of modularity, without outlining whether these benefits are universal or context-specific. Inspired by contingency theory, I reason that the strength and nature of the performance effects of using product modularity in a manufacturing firm depends to a large degree on its internal and external context. That is, the appropriate level of modularity is likely to be dependent on numerous factors, many of which can already be found in existing research. However, research on these contingency factors is rather scattered, and little research directly address how these factors influence the performance effects and applicability of modularity in manufacturing firms. By consolidating existing research, this thesis identifies contextual and firm specific factors that are likely to influence the applicability of modularity and outlines manufacturing, product development and integrative practices that potentially influence the modularity-performance relationship.

To test hypothesized linkages between product modularity and performance, as well as specify the contexts wherein modularity indeed works best, the thesis takes its outset in survey research. Three separate questionnaires form the basis for this survey research. The majority of the empirical evidence derives from the international manufacturing strategy survey (IMSS), an international survey with the purpose to study the development and performance effects of different manufacturing practices around the globe every four to five years. The most recent round of data collection occurred in 2013, and provides data from over 800 firms from 21 different countries. For the Danish data collection, an additional section was added to the IMSS (IMSS-DK), designed to support the research reported in this thesis; a section detailing the performance of, and use of actions programs in, product development. Around 40 firms provided answers to this IMSS-DK section. In addition to IMSS data, the thesis also uses response data from around 140 Swedish firms. This data was collected through a survey of Swedish product development practices (SPDS) in 2014/2015.

The remainder of the discussion is structured as follows. First, it recalls the effects of modularity on a range of operational dimensions and describes how the environment can create urgency for and drive firms towards modularity. Then, the relationship between modularity, the organization of work, and performance is explained, delineating between how modularity influences a) the organization of manufacturing tasks, b) the organization of product development tasks, c) and the integration of product development tasks.

8.1. PERFORMANCE EFFECTS OF PRODUCT MODULARITY

The review of existing studies researching the effects of modularity on performance revealed that the practice has been proven to have a positive impact on overall financial and operational performance. However, survey research and later theory development studies do not find a clear link when it comes to modularity and its impact on specific performance areas, including cost and quality performance.

In line with other survey-based research, the results of the thesis showed modularity to have a positive influence on cost, flexibility, delivery and service performance. The IMSS indicates that modularity leads to lower manufacturing unit and purchasing costs and higher mix and volume flexibility, faster delivery speed and higher delivery reliability, better customer service quality, and increased product customization and product assistance and support capability. Increasing the modularity of the product portfolio is, thus, a way in which manufacturing firms can combine cost-efficient production with increased product flexibilities and customer responsiveness.

More research is, however, needed to establish the effects of modularity on time and quality performance. In order to do so, that research should distinguish between the time performance of different manufacturing processes (manufacturing, assembly, delivery) and product development processes (new product development, product variant development, product improvement). Also, it should encompass different dimensions of quality, including both external product quality measures (e.g. design quality, reliability, durability, conformance to customer expectations) and internal process quality measures (scrap and rework rate, conformance to expectations).

In addition to research regarding *what* effects that can be expected from the implementation of modularity, research is also needed to establish *when* these effects occur. More specifically, future research is needed that details when and how different types of firms can offset the initial costs of developing modular systems and achieve superior performance by pursuing modularity.

8.2. ENVIRONMENTAL AND ORGANIZATIONAL CONTEXT

There is a notable lack of research addressing environmental contingency factors influencing the use and applicability of modularity in different contexts. Even more so, the contingency factors that have been proposed have seldom been empirically tested. Given the immature nature of this research area, this thesis turned to existing modularity theory as well as well-known contingency variables to identify the environmental context wherein the use of product modularity is prevalent. Consolidating the suggestions of existing theory, the literature proposes firms to benefit most from modularity in heterogeneous and dynamic environments.

Firms are more inclined to pursue modularity when they have higher product complexity, and experience customer heterogeneity (increased demand for product customization and larger market spans) and higher rates of technological change, growth in market size, and competitive rivalry (higher market concentration, competitive rivalry, higher customer bargaining power). Based on these findings, and the general modular systems theory (Schilling, 2000), the thesis proposes the rate of technological change and market demands for customization to be primary drivers behind the adoption of modularity, whereas the degree to which a firm experiences competitive rivalry and growth in market size are forces creating the urgency to do so. In other words, the former two factors constitute the primary pressures that affect the value a firm can achieve by pursuing modularity, whereas the latter two factors are proposed to increase the likelihood of responding to these pressures. This proposition, however, requires further research.

Further research is also needed to detail the found relationships; including research into the degree and types of *demand* heterogeneity modularity can and cannot support, and research that addresses the type of contexts in which modularity presents a fruitful strategy for providing customization and product variety. Further, more research is needed to detail the relationship between modularity and *input* heterogeneity in terms of whether and, if so, why modularity is more prevalent or useful in environments with heterogeneous inputs.

The thesis contrasts several other reports on the found relationship between modularity and environmental dynamics. Even though the results indicate that the use of modularity is related to a higher rate of technological change, no relationship between the practice and other forms of environmental dynamics (including the rate to which the firm experiences and exhibits demand variation) was found. The relationship between modularity and environmental dynamics, thus, needs further research, including an investigation of a) the nature of this relationship, b) whether and how modularity can be combined with other practices to cope with dynamics, c) and whether and how environmental dynamics in combination with other environmental factors influences the adoption rate of modularity.

Last but not least, the thesis' findings indicate that firms with high use of modularity also experience higher supplier bargaining power. While other dimensions of competitive rivalry probably are factors that result in the adoption of modularity, the relationship between modularity and supplier bargaining power might be opposite. In particular, by standardizing components and interfaces, firms, unintentionally or perhaps not, create the possibility not only for competitors but also for suppliers to relatively easily imitate the overall product design, which, in turn, increases supplier bargaining power.

8.3. MODULARITY AND THE ORGANIZATION OF WORK

Table 49 presented the two core assumptions of existing modularity research. Although the main focus of the thesis is on detailing the relationship between modularity and performance (*cf. core assumption 2),* in an effort to do so, the relationship between modularity and the organization of work *(cf. core assumption 1)* plays a central role.

In particular, in order to explain *how* modularity influences the performance of the manufacturing firm, this thesis examines how this relationship is influenced by:

1) The organization of manufacturing tasks.
2) The organization of product development tasks.
3) The integration of product development tasks.

8.3.1. ORGANIZATION OF MANUFACTURING TASKS

In explaining the effects of product modularity on performance, theorists often assume or propose the use of modular products to enable process modularity, which, in turn, enables firms to overcome the presumed trade-off between low manufacturing costs and high end-product variety. That is, modularity is proposed to allow the firm to separate the forecast-driven mass-production of semi-finished goods and modules from the final manufacturing and assembly tasks, which can be conducted based on specific customer orders. The data supports this proposition: firms with higher levels of modularity are more inclined to assemble-to-order. The data also confirms the hypothesis that the positioning of the CODP influences (some of) the performance effects that can be achieved by using modularity. In addition to increasing quality and delivery reliability performance, using modularity in ATO environments also leads to better processing related performance (i.e. increased delivery and procurement speed, lower manufacturing unit and ordering costs), whereas MTO manufacturers become more responsive to customers (volume and mix flexibility, product customization ability, product assistance and customer service quality). Thus, firms that position their CODP further downstream (e.g. ATO), use modularity to achieve economies of scale benefits and firms with a more upstream positioning of the CODP (e.g. MTO) utilize the practice to increase their customer responsiveness. The data also shows that DTO manufacturers benefit from implementing modularity: DTO manufacturers with high use of modularity perform significantly better in terms of introduction ability, service quality, ordering costs and procurement lead time.

The use of modularity in design- or engineer-to-order environments is an area that has received little attention so far. Research could therefore benefit from a further explanation of differences between how DTO, MTO and ATO manufacturers adopt modularity, detailing under what conditions modularity is an appropriate solution for these manufacturers, with particular emphasis on how DTO manufacturers can use this practice.

8.3.2. THE ORGANIZATION OF PRODUCT DEVELOPMENT TASKS

In addition to affecting the organization of manufacturing tasks, the use of a modular product architecture is also expected to allow for a modular organization of product development tasks, where independent design entities can conduct detailed design activities autonomously and concurrently. Although debated in the modularity literature, some authors even propose that modularity gradually will lead to market modularity, where, instead of taking place within the firm, product development and innovation tasks are conducted in a broader network of suppliers and competitors.

The present research does not find unequivocal evidence for the link between product, organizational and market modularity. Although data from the IMSS-DK does indicate that firms that have adopted modularity also conduct parallel product development, these results are not significant. Furthermore, no significant relationship between the use of product modularity and the outsourcing of product development tasks is detected. Therefore, more research is needed to establish how modularity influences the organization of development tasks, including research into how the practice influences the organization of different types of product development processes, and research that establishes when and how modularity leads to organizational and market modularity.

8.3.3. THE INTEGRATION OF PRODUCT DEVELOPMENT TASKS

Existing survey research focusing on the role of practices in the relationship between modularity and performance, is predominantly limited to variables reflecting the degree of integration or coordination the firm exhibits between functions or with customers, suppliers and/or other partners. Even within this limited research area, the researchers do not agree whether integration is a predecessor to successful modularization, or instead constitutes a mediator or moderator in this relationship.

The authors proposing integration to be an antecedent or moderator in the modularity-performance relationship argue that the success of modularization efforts depends on the firm’s ability to encompass different functional and processing requirements in its design effort, as well as the degree to which it understands customer preferences and supplier capabilities. However, these authors are not able to convey why integration is important for modularity efforts per se. Since all product design efforts are inherently interdisciplinary, all require some degree of internal and external integration. Therefore, the thesis proposes integration to play a more important role as mediator. Creating a modular product system is, in large part, an exercise in the standardization of interfaces. That is, modularization requires the firm to externalize and codify key information about how the modules are to interact. By restricting the communication between design entities to the design rules embedded in the interfaces, modularity can be expected to support the integration of product development tasks, enabling design teams to communicate more clearly, with less effort and more frequently. Evidence from the IMSS supports the proposition that integration is a mediator in the relationship between modularity and performance. Modularity not only influences cost/speed, quality, delivery, flexibility and service performance directly, it also has indirect effects on performance through integration. In other words, the findings suggest that modularity is a mechanism by which cross-departmental internal integration and external integration with suppliers and customers can be increased, which in turn increases performance in a number of areas.

In addition to testing the role of modularity as an integration mechanism, the thesis also studies the relationship between modularity and other organizational and design practices commonly used to coordinate the product development process. Existing empirical evidence suggests that modularity in itself does not provide enough inter-functional and cross-boundary integration, and that firms should also rely on other mechanisms to align module interfaces. The data does not suggest modularity to be commonly instituted in combination with known organizational coordination mechanisms. That is, no association was found between the use of modularity band the use of cross-functionality, co-location, formalization, the stage-gate model, and agile work arrangements. However, modularity does seem to be complemented by the use of other design practices known to support concurrent engineering, including the use of product platforms, technological readiness classification, and quality function deployment (QFD). The finding that modularity often is combined with the use of platform thinking and QFD is not surprising. QFD can assist in ensuring that customer preferences are taken into consideration early on during the design of modular products. Modularity, in turn, supports platform thinking; it plays an essential role in standardizing the components in the product platform and defining the interfaces by which the platform is decoupled from other variable, peripheral components. The use of TRL classification combined with product modularity, however, is a topic less treated in existing literature, and is, thus, an interesting area for further research.

8.4. CONCLUSION

The research presented and discussed in this thesis set out to study the effects of modularity on performance, and determine how environmental context and the organization of work during product development and manufacturing influences that relationship. Using three surveys, important findings were produced, showing that modularity has positive direct effects on operational performance.

Independent samples t-tests indicated that firms with a high adoption of modularity have better product quality and reliability, conformance and customer service quality, product assistance, volume and mix flexibility, product customization and introduction abilities, delivery speed and reliability, manufacturing unit cost, manufacturing and procurement lead time, as well as higher product variety. Based on a further grouping of firms according to whether they primarily use DTO, MTO, ATO, and PTS, additional t-tests revealed the positioning of the CODP to impact the relationship between modularity and performance. In addition to realizing superior quality performance, ATO manufacturers were shown to primarily achieve processing related advantages (delivery, manufacturing and ordering performance), whereas MTO manufacturers attained market-oriented benefits from using modularity (delivery reliability, flexibility, customization, and service performance). DTO manufacturers were also found to benefit from modularity; the use of modularity by these manufacturers results in better introduction abilities, increased customer service quality, and lower procurement costs and lead-time.

Based on factor analysis, the IMSS performance items[6] were grouped into five dimensions, covering the cost/speed, flexibility, quality, service, and delivery performance of manufacturing firms. Regression analysis showed the practice to positively impact these performance dimensions. This relationship between modularity and performance was found to be both directly and indirectly, i.e. through internal integration, customer integration and supplier integration. With the exception of customer integration in the relationship between modularity and cost/speed performance, all three types of integration were found to (partially) mediate the relationship between modularity the five aforementioned performance dimensions.

[6] The item ’introduction ability’ was not included in the factor analysis.

Furthermore, the influence of a range of contingency factors was investigated. T-tests indicated that firms are more inclined to pursue modularity when they have more complex products, and experience more customer heterogeneity, higher rates of technological change, growth in market size, and more competitive rivalry. Based on these findings, I suggest the technological rates of change and market demands for customization to be primary pressures driving the adoption of modularity by affecting the value a firm can achieve by pursuing the practice, whereas competitive rivalry and market growth are factors creating urgency, impacting the likelihood that firms will react to these pressures.

Finally, several suggestions for further research were formulated. Some suggestions follow from tentative explanations for surprising findings; others stem from the limitations of this study.

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APPENDIX

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PAPER 1 - PRODUCT MODULARITY AND ITS EFFECTS ON THE PERFORMANCE OF MANUFACTURING FIRMS

Boer, H. E. E. and Hansen, P. H. K. (2013)

"Product modularity and its effects on firm performance: Operationalization and measurement"

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Boer, H. E. E. (2014)

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PAPER 3 - CONTRASTING PLATFORM THINKING AND PRODUCT MODULARIZATION

Boer, H. E. E. and Persson, M. (2014, June)

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PAPER 5 - DESIGN-FOR-VARIETY AND OPERATIONAL PERFORMANCE

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