Department of Management and Engineering
Master's Programme in Manufacturing Management
LIU-IEI-TEK-A--08/00312--SE

Postponement, Mass Customization, Modularization and Customer Order Decoupling Point: Building the Model of Relationships

by

Kemal Caglar Can

Postponement, Mass Customization, Modularization and Customer Order Decoupling Point: Building the Model of Relationships

Master Thesis

Department of Management and Engineering
Linkoping University
Institute of Technology

by

Kemal Caglar Can

(LIU-IEI-TEK-A--08/00312--SE)

Supervisor

Professor Jan Olhager (IEI)

Foreword

It was a really great experience for me to study Manufacturing Management Master Program in Sweden. Not only the courses were interesting, but also the social life, learning different cultures and meeting people from all around the world have ensured me a fantastic period of one and a half year. I could not even imagine that I would have such a wonderful time in the land of Vikings.

After a one year of tough courses, I would be able to start this master thesis. In order to have a successful master thesis, I have tried to use the related knowledge that I gained from courses. I believe that I have improved both my professional skills and personal skills during my courses and thesis study.

First of all, I would like to thank to Swedish Institute for affording all my expenses during my master study. My study abroad dream would not come true without their financial support. I also want to express my gratitude to Jan Olhager, my supervisor for helping and guiding me during all the thesis period. My project partner for many of my courses, Iuliana David deserves great thanks from me not only for being a hard-working partner, but also for checking the grammar and spelling errors in my thesis. Finally, I would like to thank to Burcin Ugur for bringing me the sunshine in the cold and dark winter days of Sweden. It would be very hard to finish the thesis on-time without the motivation she provided me.

Thank you very much.

Kemal Caglar Can

Linköping, January 2008

Abstract

This paper focuses on four interrelated strategies: postponement, mass customization, modularization and customer order decoupling point. The goal of the postponement is to delay the customization as late as possible in the supply chain. It is also known as delayed differentiation. Mass customization is a relatively new term, which began to gain attention in the industry a decade ago. It was an obligatory invention as a response to the global market which becomes more turbulent day by day for the last two decades. Its goal is to produce customized products at low costs. Modularization is a common term that is used in many areas. In this study, we will focus on product architecture modularity and process modularity. Customer order decoupling point, which is also known as order penetration point, is used to distinguish the point in the supply chain where a particular product is associated to a specific order.

Our target is building a model that explains how these four concepts are related. In order to achieve this, we will, first, research every concept individually; we will state the definitions, levels, benefits, enablers, success factors, drivers, etc. of the concepts. Then we will study the pair-wise relationships of these strategies. We will build our model according to the findings we have found in the literature. After building our model, we will explore it in Autoliv Electronics to see how it works in practice.

Briefly, our model states the following:

Modularization is an enabler of customization and it is necessary for the success of mass customization where set-up costs are critical. Product architecture modularity provides rapid assembly and cost efficiency that is required for postponement and mass customization. In addition, it is used to measure the mass customization degree according to some others.

Postponement requires process modularity, and it moves the customer order decoupling point downstream in the value added material flow. It contributes the mass customization by increasing both the leanness and agility.

Customer order decoupling point uses the customer requirements and existing capabilities of the mass customization for optimizing the flexibility-productivity balance.

Table of Contents

Index of Figures

Index of Tables

1. Introduction

The tradeoff between price and customization of a product is long-run debate, perhaps as old as the beginning of the industrialization. It is common knowledge that the closer the product specifications are to customer demand, the higher the value of it for the customer. It is not an easy task to meet every individual's needs in today's turbulent and volatile market environment. Because the media, especially internet, now enables customers to reach any manufacturer that produces exactly what he/she wants, it is not also easy to survive without meeting exact demands of the customers. In order to understand the current situation, we will first describe how the industries came to this point.

From the introduction of Model T by Ford (the beginning of 20th century) to 70's, the main competitive priority was cost and manufacturing firms were focusing on price to improve profitability and market share. Single-purpose and high volume manufacturing on the assembly lines was dominating industries by providing efficiency and productivity. Manufacturing systems of this mass production era can be characterized as high start-up cost, top-down rigid information flow, sequential product layout, high degree of automation, low-skilled tasks, and exploitation of economies of scale (Kumar 2004).

In the late 60's and the early 70's, customers started to be willing to pay more for a customized product. They were tired of standard products, poor quality, and long delivery times. Customers were demanding product variety, but manufacturing systems were not designed for that. This mismatch inspired the start of academic studies about operations strategy and competitive priorities (Skinner 1969). Academicians stated that competing only based on price was not valid anymore, and competition was moved towards multi-dimensional structure, in which companies had to focus on one of the competitive priorities of cost, delivery, quality or flexibility. In this period, first studies about postponement, which is introduced by Alderson (1950), had started by Bucklin (1965). In addition, modularization started to gain attention in the industry. However, it took more than a decade to transform not only manufacturing systems, but also minds of CEO's.

In 80's, Japanese firms were the first to realize the change in the markets. By investing in flexible manufacturing systems and quality, they stepped ahead of American firms. Competitive priority shifted from cost to quality. It took a while for American and European manufacturing to implement the quality systems required for the competition. However, Japanese firms did not remain static. While European and American companies were struggling with quality problems, Japanese firms implemented flexibility in their manufacturing systems. They were challenging the single-priority based competitive battle by improving both of the competitive dimensions at the same time. In this period, first study about mass customization is published by Davis – Future Perfect (1987). Nevertheless, industries could not pay attention to mass customization because of the battle on quality.

The 80's witnessed the academic studies about postponement. Shapiro (1984), Zinn and Bowersox (1988), and Zinn and Levy (1988) investigated the effects of postponement in the supply chain (inventory position, role of power, marketing channels …). One other academic development during this period was the introduction of the Customer Order Decoupling Point (CODP) Sharman (1984) in a logistic context with the name of Order Penetration Point (OPP) (Olhager 2003).

In the beginning of the 90's, while American companies were trying to adopt flexibility in order to close the gap between Japanese companies, strategic value which could accrue from implementing flexibility were diminishing (Kumar 2004). Mass customization was a known cure, but there were no takers (Kumar 2004). Piller (2004) explains why companies did not implement mass customization during that time: While mass customization has been described and talked about for a long period of time now, adequate systems to perform customer co-design efficiently and effectively have been available only a couple of years back. The enabling technologies for customer co-design have just started to penetrate the market space (Piller 2004).

Although mass customization could not be applied in the industries during the beginning of 90's, academic studies about it were going on. Pine published "Mass Customization: the New Frontier in Business Competition" in 1993. Postponement, modularization and CODP gained attention from academic perspective as well as the industrial perspective. Bowersox (1995) proposed that postponement implementation had increased from the beginning of 90's. In the field of modularization, academicians (Chen 1987, Ulrich & Tung 1991, Pimmler & Eppinger 1994, and the others) were guiding the industry. CODP concept was its early development phase. Vollmann et al. (1997) and Hill (2000) developed the concept of OPP (CODP) proposed by Berry and Hill (1992) (according to Olhager 2003).

Internet began to reshape the world at the end of 90's. According to Kumar (2004), internet had two significant impacts strategically: (1) entry barriers and (2) exit barriers disappeared. Companies which are good at all four priorities can easily penetrate any market in the world by just building a web-site with a small investment. Conversely, a company that has any competitive skills lacking can loose a big market share, and even disappear. The ubiquitous presence of Internet has, therefore, created an aura where companies can no longer afford to compete on just one priority; there is always someone who can compete on all four priorities and win the competitive battle (Kumar 2004). But, how can companies compete in all four fields (cost, delivery, quality and flexibility)? Kumar (2004) states that mass customization strategy, when thoughtfully implemented, would produce a winner in all competitive priorities, partly through product design (customization), partly through web-based customer interaction (customer satisfaction), and remaining through appropriate production systems associated with mass customization strategy (cost, quality, and delivery).

Comstock (2004) describes the current attributes of the market as following:

- Customers are no longer a homogenous base.
- Customers demand specific products to suit their specific needs.
- Product life cycles are significantly shorter.
- Basic products are differentiated by options.
- New families of products are highly configurable.
- Assemble to order is becoming a strategy of market leaders.
- Customer responsiveness can not be achieved through the simple build-up of inventories.
- Potentially greater profit margins can be made in customizing products.

(Comstock 2004)

We can summarize the major events about the concepts in the following timeline (Figure 4). We have been inspired by Comstock (2004) for doing a timeline, but we have included not only mass customization, but also postponement, modularization and customer order decoupling point (CODP or OPP). We only included major events briefly, thus eliminating some less major events. We think that this timeline is useful to understand the relative development of concepts.

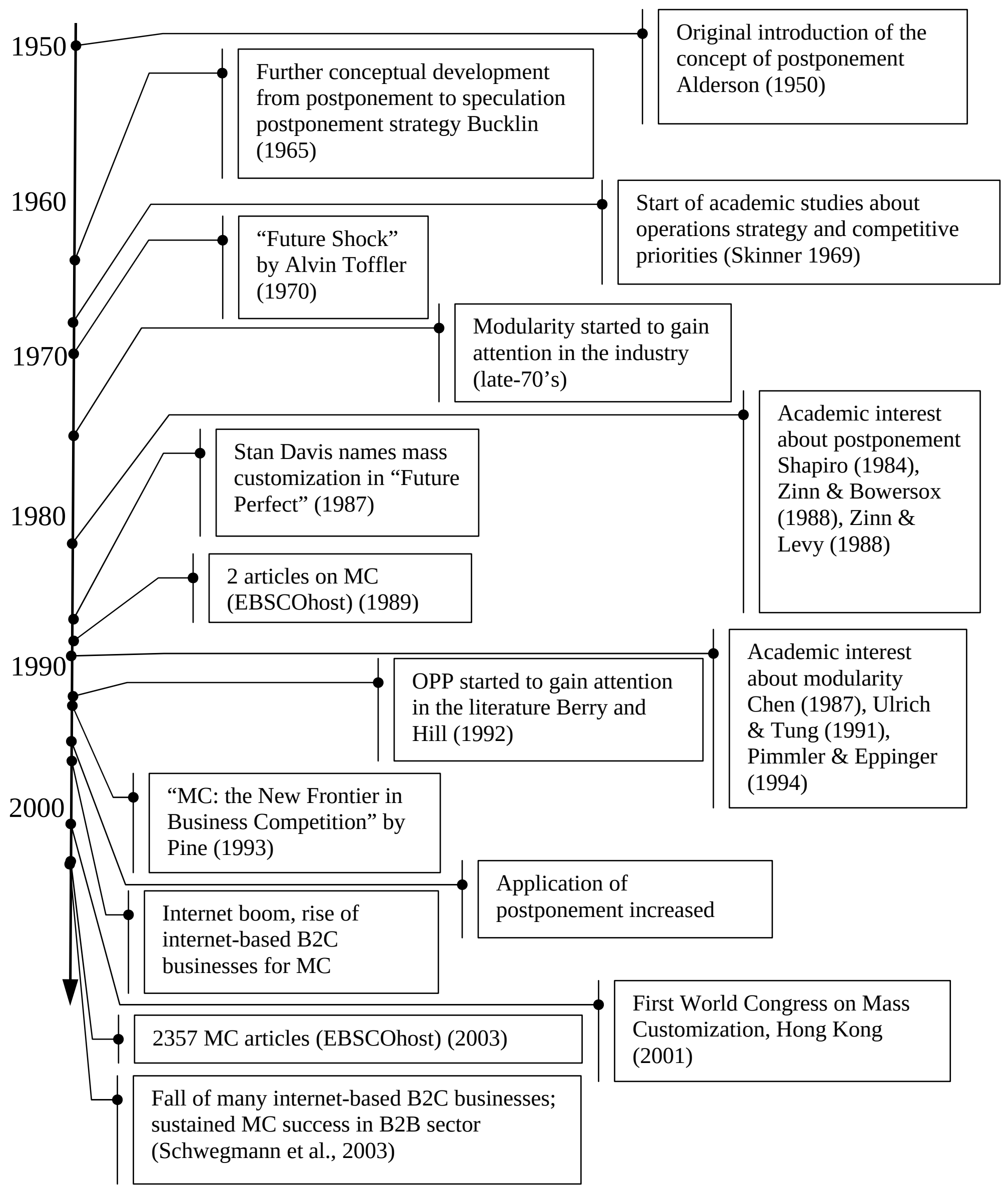

Figure 1-1: Timeline for the four concepts

(Mass customization, postponement, modularization and CODP) (inspired from Comstock 2004)

The aim of this master thesis is to explain how mass customization, postponement, modularization and CODP are related to each other, and to build a model that indicates these relationships. In order to achieve this, we will first describe every concept individually in Chapter 2. In Chapter 3, we will investigate the pair-wise relationship of concepts. We will combine the relations of the concepts in a matrix formatted table in Chapter 4. Then, according to this table, we will present our model in a model chart and on an illustration figure in Chapter 4. In Chapter 5, we will try to observe the relationships, mentioned in Chapter 3 and 4, in a company as well as try to verify our model. In the last chapter, Chapter 6, we will conclude our thesis with our finding about the concepts, implications for researchers and managers, future research options and recommendations.

2. Individual Concepts

In this chapter, we try to explain every concept individually. The aim of this chapter is to provide a better understanding of the concepts for the reader. A comprehensive literature review of the four concepts is carried out; and according to the literature review, we will mention the important topics related to the concepts.

2.1 Postponement

In order to be able to compete in today's customer-driven markets, companies try to serve products which exactly fit specific requirements of every customer. When companies have a large variety of products, which are designed to fit many different customer demands, it is not cost efficient to keep them in stock. As well, by keeping stock companies are faced with the obsolescence risk. Moreover, when time is a competitive factor, markets demand producers to be more responsive by providing short and reliable lead times (according to Bhattacharya et al. 1996 as stated in Skipworth et al. 2004). Postponement is a concept which brings the efficiency of the lean concept and the responsiveness of the agile concept together (Van Hoek, 2000).

In this section, we will first mention the definition of postponement. Then, we will classify some different postponement strategies. Later, we will investigate the factors hiding beneath the implementation of postponement. Finally, an explanation on how postponement is used as a tool of managing uncertainty will be provided.

2.1.1 Definition

Van Hoek (2001) gives the following definition:

"Postponement means delaying activities in the supply chain until customer orders are received with the intention of customizing products, as opposed to performing those activities in anticipation of future orders."

According to this definition, companies can delay distribution, packaging, assembling, production or even purchasing until they receive exact customer orders. Van Hoek (2001) gives several examples for the different locations of postponement in the supply chain. For example, MCC (a Daimler Chrysler car company) and Dell wait until receiving customer orders to purchase parts from their suppliers. Mars (a Masterfoods company) does not finalize its products in Christmas session so that packaging is carried according to the customer demand.

Logistics (distribution) postponement is another extreme of postponement compared to purchasing postponement. Bowersox (1978) states that before distributing products, information of level and place in the customer order includes an opportunity to decrease the distribution cost (Yang et al. 2004a). It means distributing products with the exact information of place and quantity creates the opportunity of cost savings compared to the distribution with no exact order. According to Bowersox et al. (1993), logistics postponement offers chances to locate inventory in any other place at any other time, which decreases risk of being wrong (Yang et al. 2004a). In other words, if the company waits the exact order to distribute the products to local or international warehouses, it reduces the risk of delivering products more than or less than needed.

Yang et al. (2004a) assert that the main target of companies for postponement application is usually to decrease distribution cost. He gives the example of HP which saves 3 million $ per month from the logistics cost by postponement. On the other hand, in the same article, Yang et al. (2004a) state that transportation costs can increase because the logistics postponement requires "fast and responsive transportation system". They claim that in addition to just physical transportation of products, when the customization of products is the case, companies get the highest advantage. This is consistent with the example of HP which finalizes the DeskJet printers according to the customer specification in the local warehouses.

2.1.2 Classification of Postponement Strategies

Mainly three types of postponement strategies are mentioned in supply chains: time postponement, place postponement and form postponement. Bowersox and Closs (1996) define these as following:

> *"Time postponement: delaying the forward movement of goods until customer orders are received (delaying the determination of the time utility);*
>
> *Place postponement: storage of goods at central locations in the channel until customer orders are received (delaying the determination of the place utility);*

Form postponement: delaying product finalization until customer orders are received (delaying the determination of the form / function utility)"

(Van Hoek 2001)

In the article "Management of uncertainty through postponement" (2004b), Yang et al. mention the classification of postponement strategies (Table 2-1). According to this article, Zinn and Bowersox (1988) classify postponement strategies as form postponement and time postponement; Bowersox and Closs (1996) classify these as logistics postponement (time and place postponement) and manufacturing (form) postponement; Lee (1998) uses a classification of pull, logistics and form postponements; and Waller et al. (2000) groups postponement strategies as production postponement, upstream postponement and downstream postponement. In the same article, Yang et al. (2004b) analyze postponement strategies in terms of uncertainty and modularity. They arrange postponement strategies into four categories: purchasing postponement, product development postponement, logistics postponement and production postponement. We will mention these in the section of "postponement as a tool of uncertainty management".

References	Classification of postponement strategies
Zinn and Bowersox (1988)	Form postponement (including manufacturing, assembly, packaging and labelling postponement) and time postponement
Bowersox and Closs (1996)	Logistics postponement (combination of time postponement and place postponement) and manufacturing/form postponement
Lee (1998)	Pull postponement, logistics postponement and form postponement
Waller *et al.* (2000)	Production postponement, upstream postponement and downstream postponement

Table 2-1: Literature review of classification of postponement strategies

(Yang et al. 2004b)

For assorting postponement strategies, Yang and Burns (2003) follow a different approach which is based on Lampel and Mintzberg (1996). The point where speculation and postponement strategies are separated in the supply chain is used to name the postponement strategy. From upstream to downstream, the sorts of postponement are purchasing postponement, manufacturing postponement, assembly postponement, packaging (labeling) postponement, logistics postponement (Figure 2-1). This classification also gives an idea for the relationship between customer order decoupling point (CODP) and postponement (Yang et al. 2003), which we will mention later.

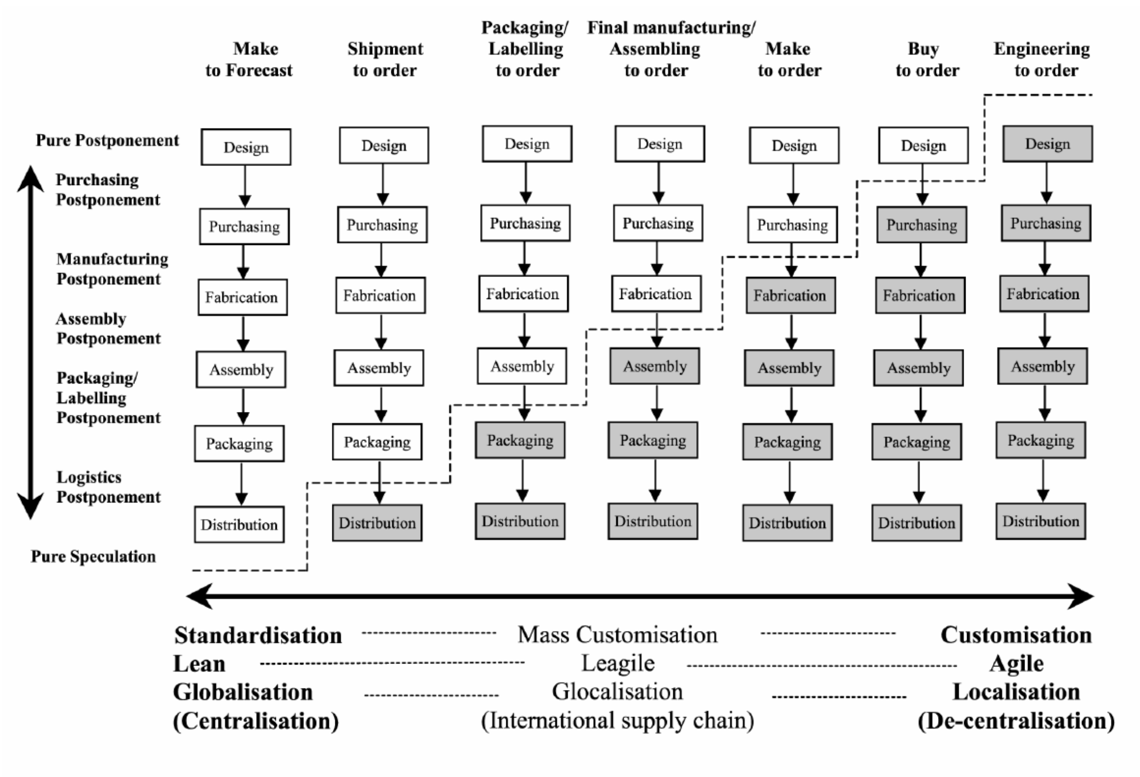

Figure 2-1: Speculation-postponement strategy and a continuum of standardization-customization (Yang et al. 2004a)

2.1.3 Drivers and Benefits of Postponement

According to the survey, which is included in Van Hoek's article (2000), companies tend to implement postponement in order to increase the performance of both efficiency and responsiveness in the operational level. Companies voted the drivers of postponement in the descending importance order as following:

- Raising delivery reliability
- Improving speed of delivery
- Improving inventory cycle times
- Lowering logistics cost

- Lowering obsolescence risk
- Improving product customization

In the literature, many different research methods, such as surveys, cases and simulation studies are used to calculate the benefits of postponement. Davila et al. (2007) assert that simulation studies proved a decrease in inventory levels and manufacturing lead-times. A survey evaluated by Nair (2005) shows that "better asset productivity, delivery performance and value chain flexibility" are considered as benefits acquired via the implementation of postponement by companies (Davila 2007). According to the cross-case analysis conducted by Krajewski et al. (2005), one possible application area of postponement is the reduction of uncertainty due to "the short-term dynamics in the supply chain" (Davila 2007). Based on the case study of Brown et al., Xilinx (a semiconductor company which implements product and process postponement) enjoys the lower inventory levels; at the same time customer service remained the same (Brown et al. 2000 – Xilinx). Another case analysis is conducted by Skipworth and Harrison (2004) in a high-voltage cabling company. They have found that responsiveness is improved by form postponement, but not the delivery reliability. They also mention the problems during the implementation of postponement. Avin and Federgruen (2001) claims that keeping stock of generic product modules requires fewer safety inventories than keeping several specific finished products inventory and this reduces the inventory and improves the service as a result of risk pooling (Davila & Wounters 2007).

Although Skipworth and Harrison (2004) claim that postponement doesn't improve the performance of delivery reliability, Davila and Wounters (2007) find that the higher postponement utilization increases the on-time delivery performance and results lower variable cost (operational cost). They have measured the level of postponement utilization by the percentage of the generic products shipped. They also state that the company in which they conducted the case study preferred the customer service side in the trade-off between inventory turns and on-time delivery. They preferred to keep inventory turns at relatively acceptable levels while improving on-time delivery (customer service).

	Traditional operations	Postponement opportunities
Uncertainties	Limit operations; uncertainty about order mix and volume	Reduce risk of volume and variety mix by delaying finalization of products
Volume	Produce volumes with large economies of scale	Make batches of one (job shop for customization, flow shop elsewhere)
Variety	Create obsolescence risk	Prosume, customize, requiring flexibility
Lead times	Involve long response time	Offer accurate response, yet perform activities within order cycle time
Supply chain approach	Limit variety to gain efficiency advantages	Reduce complexity in operations, yet possibly add flexibility and transport costs

Table 2-2: Postponement opportunities in operations (Van Hoek 2001)

Van Hoek (2001) exemplifies this in Table 2-2 with a comparison of Volkswagen (traditional operations) and MCC (postponement approach). He claims that large volumes are important for the efficiency in Volkswagen, but its customers suffers from long lead times and poor service because of this. Higher product variety in Volkswagen results higher obsolescence risk. On the other hand, MCC (a Daimler Chrysler company) provides customized cars which are assembled one by one, although modules are produced in flow shop style. The risk associated with inventory and variety is reduced by storing only generic modules. Prosuming means involving the customer in production, in MCC case by having the customer virtually specify the bill of materials (Van Hoek 2001). Compared to the Volkswagen customers, MCC customers wait shorter lead times to drive their cars (Table 2-2).

2.1.4 Postponement as a Tool of Uncertainty Management

Yang and Burns (2003) see postponement as one of the tools to deal with uncertainty. They believe that two main ideas are behind the postponement concept. First, it is easier to forecast aggregate demand compared to forecasting demand of every finished product. And second, more accurate information (place, time and quantity) can be obtained during the delay period. By redesigning the business processes according to the postponement strategy, they believe that companies can get the missing information which is the reason for uncertainty. Further, they have investigated the relationship of postponement and uncertainty in the integration of supply chain.

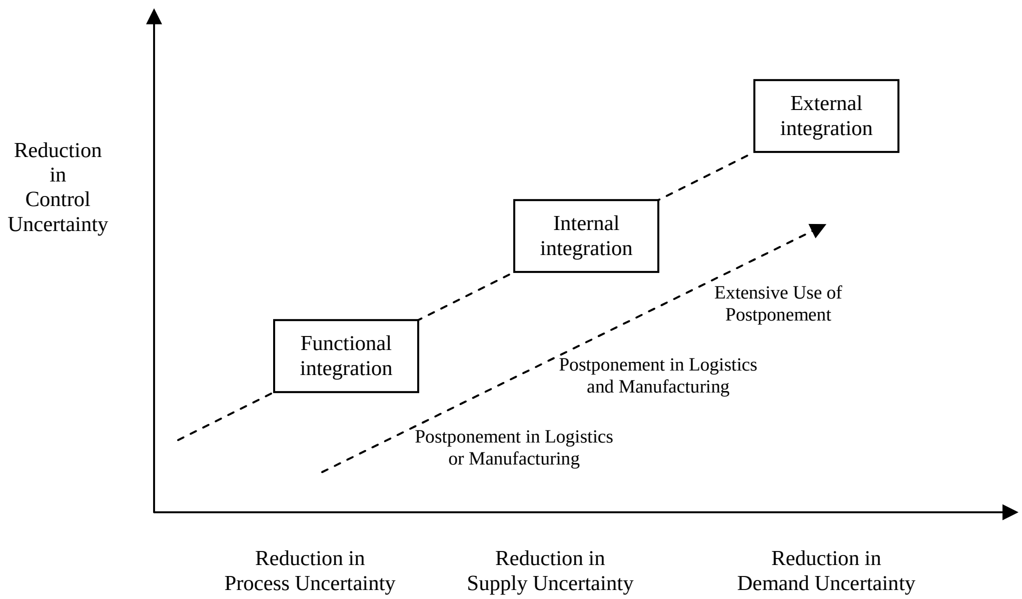

Figure 2-2: Postponement and uncertainty in improving supply chain integration (Yang & Burns 2003)

Yang and Burns (2003) recommend a three-step methodology for the integration of postponement in the supply chain. Because the firm's own processes are the most apparent and easier to modify, the first step is reducing the process uncertainty (for example cycle times). Second step is to reduce supply uncertainty (supply quality, on-time deliveries) by using logistics and manufacturing postponement. And the third step is reducing customer-oriented uncertainties, demand uncertainty (customer behaviors, market turbulence). Extensive use of postponement is required to achieve external integration of postponement, like finalizing products in customer sites and synchronized material transfer. By following these steps, control uncertainty (uncertainty in internal decision making) will be investigated through supply chain and as a consequence, it will be easier to reduce it (Figure 2-2).

Yang, Burns and Backhouse (2004b) investigate the relationship between postponement and uncertainty and how to deal with uncertainty. They state two level of uncertainty: low level of uncertainty (place and time utility of the customer order, individual demand forecasts of the finalized products while aggregate demand is more accurate) and high level of uncertainty (quantity and time utility of production and what to produce). They mention four postponement strategies: purchasing postponement, product development postponement, production postponement, logistics postponement. They claim that when high levels of uncertainty exist, it is more appropriate to implement product development postponement or purchasing postponement. These postponement strategies require no physical inventory. As well, they claim that production postponement and logistics postponement is more appropriate in the existence of low uncertainty.

2.2 Mass Customization

Yesterday's stable mass market which requires mass production (large volume & single purpose production, smooth material flow, compete on cost and efficiency) has been changing to volatile, unpredictable markets (Hart 1994). When Davis (1987) introduced the concept of mass customization (Piller 2004), he also explained how markets will be transformed from local isolated markets to "markets of one", individual niches (Comstock 2004). Advances in the communication technologies enable customers to interact with the manufacturers and demand the products that exactly fit their requirements, wherever and whenever they want. So, the expectations of customers are growing steadily. And the fast development of technology shortens the product life cycles. In an environment like this, mass production system which has high fixed costs can not ensure the required response and flexibility. On the other hand, mass customizers consider the "unpredictable nature of the marketplace" not as a thread, but as an opportunity (Hart 1994).

First, we will give the definition of mass customization in this section. Then, we will explain the levels of mass customization according to classification made by Da Silveira et al. (2001). Next, success factors and enablers of mass customization will be investigated.

2.2.1 Definition

Hart (1994) proposes two different definitions for mass customization concept. The first one is the visionary definition:

"The ability to provide your customers with anything they want profitably, any time they want it, anywhere they want it, any way they want it."

Apparently, this definition reflects a utopian situation, but it is not useless. It shows what the goal of mass customizers should approach to. The second definition proposed is practical definition:

"The use of flexible processes and organizational structures to produce varied and often individually customized products and services at the low cost of a standardized, mass production system."

Duray et al. (2000) state that the definition of mass customization started to blur because of extended applications in industries and ambiguity in the initial definition. Piller (2004) mentions about this problem and proposes a final definition to solve the issue:

"Customer co-design process of products and services, which meet the needs of each individual customer with regard to certain product features. All operations are performed within a fixed solution space, characterized by stable but still flexible and responsive processes. As a result, the costs associated with customization allow for a price level that does not imply a switch in an upper market segment."

2.2.2 Levels of Mass Customization

Da Silveira et al. (2001) research the literature which tries to classify various levels of customization applications. He builds a table which summaries the classifications done by Gilmore & Pine (1997), Pine (1993), Spira (1996), Lampel & Mintzberg (1996) (Table 2-3).

Highest level of customization, design level, is achieved by cooperative projects, production and transportation of customized products for every individual customer order (Da Silveira et al. 2001). In the fabrication level, mass customizer manufactures tailored products by using predefined processes or designs. Standardized modular components are used to respond to different customer orders in the assembly level. In the fifth and fourth level, customized additional work or services are applied to standard products (Da Silveira et al. 2001). In the third level, package and distribution level, different package sizes, labels or distribution options is used to offer customization. In the second level, usage level, products, which have adaptive functions embedded, are differentiated after delivery. And finally, the lowest level of customization refers to pure standardization, in which the products have no customization (Da Silveira et al. 2001 and Lampel & Mintzberg 1996).

MC Generic levels	**MC approaches** Gilmore & Pine 1997	**MC strategies** Lampel & Mintzberg 1996	**Stages of MC** Pine 1993	**Types of MC** Spira 1996
8. Design	Collaborative; transparent	Pure customization		
7. Fabrication		Tailored customization		
6. Assembly		Customized standardization	Modular production	Assembling standard components into unique configurations
5. Additional custom work			Point of delivery customization	Performing additional custom works
4. Additional services			Customized services; providing quick response	
3. Package and distribution	Cosmetic	Segmented standardization		Customizing packaging
2. Usage	Adaptive		Embedded customization	
1. Standardization		Pure standardization		

Table 2-3: Generic levels of Mass Customization (Da Silveira et al. 2001)

2.2.3 Success Factors of Mass Customization System

Da Silveira et al. (2001) investigated the conditions that are necessary for the achievement of mass customization. He proposed six factors, two market-related and four organization-based factors.

First factor they proposed states that "customer demand for variety and customization must exist". The degree of willingness of customers to pay and wait more and the ability of the company to meet that demand are two sides of the first factor, which are essential for the success of the mass customization (according to Kotha 1996 and Hart 1996 stated by Da Silveira et al. 2001). Hart (1994) researches the same factor in the name of customer customization sensitivity. According to Hart (1994), customer sensitivity has two basic factors that determine its strength: uniqueness of the customers' needs and customer sacrifice.

Second factor states that "*market conditions must be appropriate"* (Da Silveira et al. 2001). Based on the Kotha's article (1995), Da Silveira et al. (2001) emphasize the importance of first entrance to the market as a customizer. Hart (1994) also stresses first-mover advantage under the competitive environment. He underlines loyalty of customers for the company and the competitors, company credibility and the market position as well as other market conditions.

Third factor states that *"value chain should be ready"* (Da Silveira et al. 2001). It is claimed that for a successful mass customization implementation, supply chain players (suppliers, distributors, retailers …) should be interested and well-prepared; especially the information network among themselves should be efficiently working (Da Silveira et al. 2001).

"Technology must be available" is the forth factor mentioned for the success of the mass customization (Da Silveira et al. 2001). Without the required manufacturing and information technologies, which will provide flexibility and responsiveness, a successful mass customization is impossible to achieve. *"Coordinated implementation of advance manufacturing techniques and information technology across value-chain"* is one of the preconditions that is necessary for the implementation of mass customization (Da Silveira et al. 2001).

Fifth factor for the success of mass customization states that *"products should be customizable"* (Da Silveira et al. 2001). Modularity, multi-purposefulness and continuous renovations are some methods that are used to increase customizability. It is also claimed that modularity is not essential for mass customization, but it decreases the cost and complexity.

The sixth and the last success factor affirms that *"knowledge must be shared"* (Da Silveira et al. 2001). Dynamic networks (Pine & Victor 1993), manufacturing and engineering expertise (Kotha 1996) and the ability to build the company's own product and process technology (Kotha 1995) enable the company to have a culture which creates and distributes the knowledge across the supply chain.

According to Da Silveira et al. (2001), these success factors imply that *"mass customization is not every company's best strategy"*. Certain market conditions and customer and order characteristics are required. Another implication is that mass customization implementation implies added complexity because of the requirement of knowledge-based organizational structure, process and information technology, product configuration and value chain network.

2.2.4 Enablers of Mass Customization

Comstock (2004) investigates the enabler of mass customization in three dimensions of manufacturing systems: conceptual dimension, methodological dimension and technological dimension. Further, he mentions about a hidden dimension called human/organizational enablers.

Under conceptual dimension, Comstock (2004) analyzes flexibility and efficiency concepts. He tries to find out what kind of flexibility is necessary for mass customization. He builds the Table 2-4 based on Heilala & Voho (2000).

The Table 2-4 is built according to time frame required by the manufacturing system to respond. Comstock and Winroth (2001) claim that very short, order-based reaction time is a necessity for mass customization; therefore the logical (dynamic) flexibility is an enabler of mass customization. Heilala and Voho (2000), on the other hand, see the physical (static) flexibility as a necessity for a more agile production system. They view the concepts of reconfigurability, modularity, reutilization, expandability and scalability as "higher level" enablers of flexibility and agility (Comstock 2004).

Static or Physical Flexibility	Dynamic or Logical Flexibility
Time to react: product life cycle	Time to react: very short, order
Why: • Production volume changes • New products in the same system	Why: • **Mass customization** • Lot size one
How: • Layout modifications • Size and degree modifications • Reconfigurability, reutilization • Modularity, expandability • Scalability	How: • Use of information technology • Change of control programs • Sorting and routing • Robotics, flexible automation • Human intelligence and skills

Table 2-4: Flexibility requirements by different time frames

(modification of Heilala and Voho, 2000; according to Comstock 2004)

Comstock and Winroth (2001) categorize the flexibility types as strategic flexibility (responds to the change in external environment) and operational flexibility (responds to the change in internal environment). They claim that strategic flexibility, such as product flexibility, mix flexibility, production flexibility, volume flexibility and expansion flexibility, provides the company to respond in an agile way. On the other hand, operational flexibility, such as delivery flexibility, process flexibility, programming flexibility, routing flexibility, machine flexibility and labor flexibility, provides company to enable mass customization (Comstock and Winroth 2001). Although they commit the previous arguments, they state that the relationship between flexibility, agility and mass customization is ambiguous and open to discussion (Comstock 2004).

Efficiency is the other conceptual enabler of mass customization. It represents the “mass” side of the mass customization. According to the every different definition of mass customization, it is stated that mass customization should be cost efficient or it should be as efficient as mass production.

Comstock (2004) divides second dimension of mass customization enablers, methodological enablers, into two categories: design-related and production-related enablers. In the design-related enablers, he emphasizes the importance of modular design, axiomatic design, product family architecture and concurrent design. In the production-related enablers, he mentions supply chain management, value chain, postponement, time-based manufacturing, customer order decoupling point, customer-driven design and manufacturing, lean manufacturing and collaboration.

Da Silveira et al. (2001) have also researched the enablers of mass customization. They claim that agile manufacturing, supply chain management, customer-driven design and manufacturing and lean manufacturing are the processes and methodologies that enable the mass customization.

The third dimension mentioned by Comstock (2004) is the technological enablers for mass customization. Da Silveira et al. (2001) group the technological enablers into two categories: advance manufacturing technologies and communication & network technologies. Computer Numeric Control (CNC) and Flexible Manufacturing Systems (FMS) are given examples of advance manufacturing technologies. According to Da Silveira et al. (2001), communication and network technologies that act as technological enablers of mass customization include Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), Computer Integrated Manufacturing (CIM), and Electronic Data Interchange (EDI).

Comstock (2004) mentions a fourth dimension, a hidden dimension which is consists of the other three dimensions (conceptual, methodological and technological): human/organizational enablers. He gives the example of knowledge sharing, *"which is considered as conceptual enablers of mass customization in human/organizational context"*. Collaborative communication systems and team-based structure are one of the corresponding technological and methodological enablers respectively (Comstock 2004).

2.3 Modularization

Modularization is a widely used term in many different fields such as computer science, construction, design engineering (product architecture), production and even art (Gershenson et al. 2003). In this study, we will focus on product architecture modularity and production process modularity. The core of the product architecture modularity idea is the breaking down of the product into standardized components or group of components, which is called modules. Standardization of modules yields not only the economies of scale, but it also provides an opportunity to increase product variety. Therefore, industries did not miss the concept out for the last two decades (Gershenson et al. 2003).

In this section, first we will give the definition of modularity as following the structure used to define the previous two concepts. We will try to explain different aspects of modularity in the definition part. We think that describing different types of product modularity could be useful for a better understanding of the concept. Then, we will mention the benefits of modularization strategy. Finally, we will state a few attempts of modularity measurement by academicians.

2.3.1 Definition

Ulrich and Eppinger (1995) define the product architecture modularity as: utilization of *"chunks"* (main building blocks or modules) with well-defined few interactions among themselves and with inclusion of *"one or few"* functional elements in each of them. In order to understand modularity concept, we should first ask what the module is. *"Module is the component or group of the components that can be removed from the product non-destructively as a unit, which provides a unique basic function necessary for the product to operate as desired"* (according to Allen and Carlson-Skalak 1998 as stated in Gershenson et al. (2003)). They define the modularity as the level of module utilization by minimum interaction between modules.

Marshall et al. (1998) proposed four characteristics for the modules:

1. Modules are cooperative subsystems that form a product, manufacturing system, business, etc.
2. Modules have their main functional interactions within rather than between modules.
3. Modules have one or more well-defined functions that can be tested in isolation from the system.
4. Modules are independent and self-contained and may be combined and configured with similar units to achieve a different overall outcome.

Gershenson et al. (1999) explain the interactions in terms of independence and similarities of module components, which are mentioned above, from a life-cycle point of view. They claim that, ideally, the components in a module should not interact with the other components which are not in the same module throughout the entire life of the product (independence). Also, components in the same module should work in a similar way during each life cycle stage (similarity). They explain the concept of life-cycle as stages of product development, testing, manufacturing, assembly, packaging, shipping, service and retirement. Further, Gershenson et al. (1999) suggest three aspects of modularity that increase the independence and similarity.

- Attribute Independence: By having few or no dependencies on the attributes of other module components, module components provide re-design of module with minimum effects on the rest of the product.
- Process Independence: Each task of each life-cycle process of each component in a module has fewer dependencies on the processes of external components. Process independence allows for the reduced cost in each life-cycle process and the re-design of a module in isolation if processes should change.
- Process Similarity: Components and subassemblies in a module experience the same or consistent life cycle processes. Process similarity has many benefits such as minimizing the number of modules by grouping components with similar processes, strengthening the differentiation of modules, reducing process repetition, and lowering the cost. (Gershenson et al. 1999)

One other aspect of the modularity is the degree of modularity. It is claimed that modularity is a relative property. In other words, products can be compared according to the modularity and considered as less or more modular than the other. Otherwise, it would be hard to decide if a product is modular or not without comparison. A product is considered as more modular if it includes a greater percentage of modular components (quantitative) or the components that are included are more modular (qualitative) (Ulrich and Tung 1991, Gershenson et al. 1999)

2.3.2 Types of Modularity

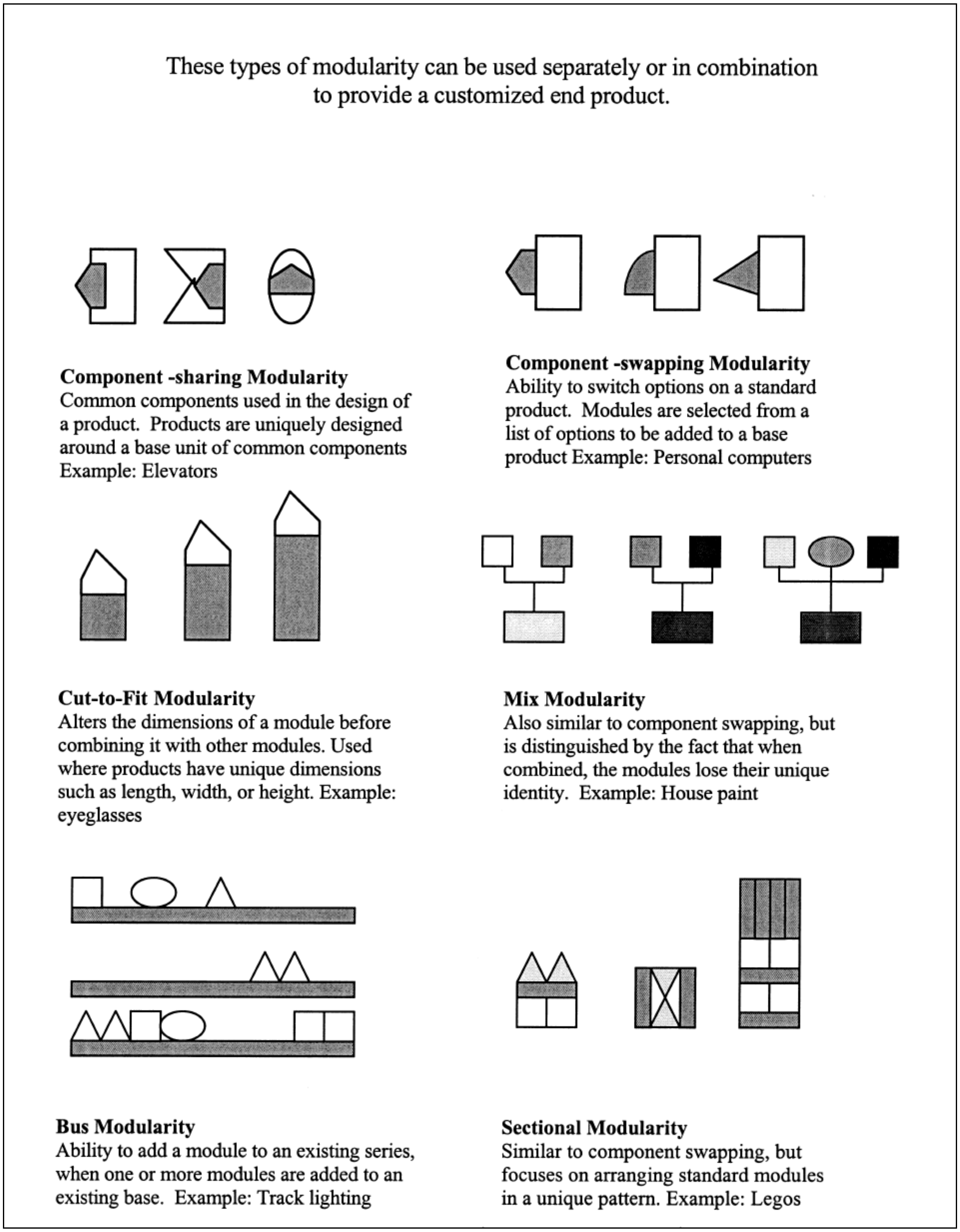

Figure 2-3: Modularity types (Ulrich and Tung, 1991 – extracted from Duray et al. 2000)

Ulrich and Tung (1991) propose six types of the modularity according to interfaces and customizability of components and arranging them (Figure 2-3). First one is component-sharing modularity. One core component is used to build many different products. The Elevator is given as an example for this type of modularity. Although the system of elevators is the same, it requires a special cabin design for every different apartment building. The second one is the component-swapping modularity. Like in personal computers, you can choose different features, which indicate different components. For example, you can choose a faster processor among many different ones. Changing the dimensions of modules, such as shortening the arms of eyeglasses for fitting the individual's face, is called cut-to-fit modularity. Mix modularity is similar to component-swapping modularity, but component properties change after mixing with other components. In bus modularity, product variants are obtained by matching any selection of components from a set of component types. Finally, in sectional modularity, product variants are obtained by mixing and matching in an arbitrary way a set of components, as in a Lego game.

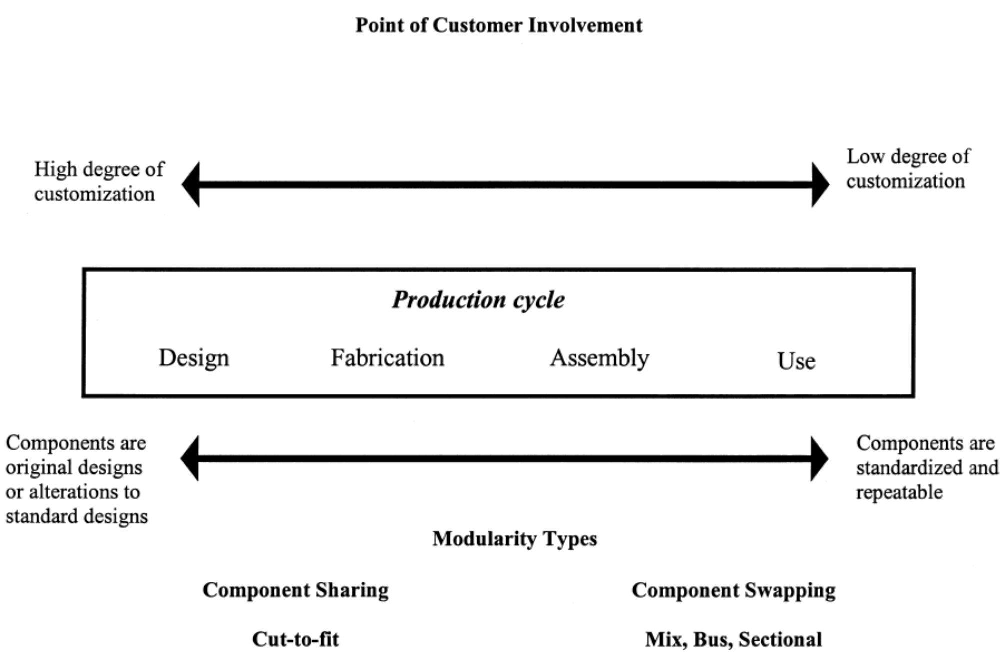

Figure 2-4: Customer involvement and modularity in the production-cycle (extracted from Duray et al. 2000)

Duray et al. (2000) have put ordered the modularity types according to the utilization in the production cycle. Component sharing modularity and cut-to-fit modularity require a new design according to the customer order. Therefore, they claim that these types of modularity should take place early in the production cycle. In addition, they state that component swapping, sectional, bus and mix modularity types use standard modules. They are assembled according to the customer order or customers use these modules according to their requirements. Therefore, they claim that these types of modularity should take place later in the production cycle (Figure 2-4).

2.3.3 Benefits of Modularization

Gershenson et al. (2003) address Ulrich and Tung (1991) as the most explicitly describing the benefits and costs of modularization. Ulrich and Tung (1991) list the following benefits and costs:

"Benefits:

1. *Component economies of scale due to the use of components across product families*
2. *Ease of product updating due to functional modules*
3. *Increased product variety from a smaller set of components*
4. *Decreased order lead-time due to fewer components*
5. *Ease of design and testing due to the decoupling of product functions*
6. *Ease of service due to differential consumption*

Costs:

1. *Static product architecture due to the re-use of components*
2. *Lack of performance optimization due to lack of function sharing and larger size*
3. *Ease of reverse engineering and therefore increased competition*
4. *Increased unit variable costs due to the lack of component optimization"*

(Ulrich and Tung 1991)

Sosale et al. (1997) investigate the benefits of modularization from different perspectives. From the product functionality perspective, it is claimed that the benefits are based on reconfiguration of modules (arranging modules in different order and adding modules) and customization (rearrangement of optional modules to create variety). From the design perspective, it is claimed that modularity allows design projects to be executed in parallel development tasks. Well-defined interfaces between modules are crucial to achieve this. Furthermore, Sosale et al. (1997) claim that fault analysis and maintenance are easier in modular products. Defective modules can be easily replaced. From the recycling, re-use and disposal point of view, because modular products are easier to disassemble, they claim that disposal, recycling and re-use are supported by modularity.

Moreover, Marshall et al. (1998) state that modularization provides efficiency and effectiveness for the following issues:

- Efficient deployment of customer requirements
- A rationalized introduction of new technology
- A structured approach to dealing with complexity
- Flexible or agile manufacturing

Mikkola and Gassmann's (2003) approach for explaining the modularization benefits depends on the comparison of modular and integral product architectures (Figure 2-5). They state that in an integral design, opposite of modular design, components are highly interdependent and any change in a component requires consequent changes in other components. They also state that the motivation of integral design is the high levels of performance. Schilling's (2000) concept of *"synergistic specificity"* supports this idea. She claims that:

> *"The degree to which a system achieves greater functionality by its components being specific to one another can be termed its synergistic specificity; the combination of components achieves synergy through the specificity of individual components to a particular configuration. Systems with a high degree of synergistic specificity might be able to accomplish things that more modular systems cannot; they do so, however, by forfeiting a degree of recombinability."* (Schilling 2000)

Benefits of Modular Designs	***Benefits of Integral Designs***
• Task specialization	• Interactive learning
• Platform flexibility	• High levels of performance through proprietary technologies
• Increased number of product variants	• Systemic innovations
• Economies of scale in component commonality	• Superior access to information
• Cost savings in inventory and logistics	• Protection of innovation from imitation
• Lower life cycle costs through easy maintenance	• High entry barriers for component suppliers
• Shorter product life cycles through incremental improvements such as upgrade, add-ons and adaptations	• Craftsmanship
• Flexibility in component reuse	
• Independent product development	
• Outsourcing	
• System reliability due to high production volume and experience curve	
Examples: Elevators, passenger cars, IBM PCs, Lego toys	***Examples:*** Formula One cars, Apollo Computers, satellites

Figure 2-5: Tradeoff between modular and integral product architecture designs (Mikkola & Gassmann 2003)

2.3.4 Measures and Design Methods

Many authors propose a matrix structure to represent the product information in modularity (Sosale et al. 1997, Newcomb 1996, Pimmler and Eppinger 1994, Huang and Kusiak 1998, Gershenson et al. 1999). In the matrix structure, columns and rows of matrix are built from components of the product. One half of the matrix is used and matrix cells are filled either with some numerical ratings or with an X that shows a relationship exists. Although filling instructions for the matrix are very well presented by guides, it still includes subjectivity. Some authors investigate the relationship of components in only one matrix (Sosale et al. 1997, Newcomb 1996); others use two separate matrices for explaining the dependency and similarity (Huang and Kusiak 1998, Gershenson et al. 1999). Gershenson et al. (2004) state that matrix representation is useful for comparison and component adjustments.

After clarifying the relationships among components, components should be categorized into modules, in other words designing product architecture phase starts. Gershenson et al. (2004) state that there are mainly four design methods for modularity: checklist methods, design rules, matrix manipulations, and step-by-step & redesign method. Some of these iterate all possibilities; some iterates according to guidelines and some constrain the iterations (Gershenson et al. 2004). Nevertheless, they claim that it is important to explore all feasible design solution.

In order to measure how modular is the product design, some authors developed formulas (Gershenson et al. 1999, Newcomb et al. 1996, Zang et al. 2001). Gershenson et al. (1999) propose the sum of the ratios of intra-module similarities to all similarities and intra-module dependencies to all dependencies as a measure of modularity. Instead of adding these ratios, Newcomb et al. (1996) multiples these to highlight that both similarity and dependency is important and they can not substitute each other (Gershenson et al. 2004). One important thing that Gershenson et al. (2004) emphasize is that existing measurement methods of modularity requires too much information and are problematic. They state that measures that require less information are necessary for concept development and layout design.

We have decided that the mention of how to measure of modularity can be useful at this point. The modularization measurement developed by Mikkola and Gassmann (2003) is a function of the number of components, the degree of coupling and the substitutability factor. We will briefly mention the formulas in this study. For detailed information and assumptions made for these formulas, see Mikkola & Gassmann (2003 – Managing Modularity of Product Architectures: Towards an Integrated Theory).

$$M(u) = e^{-u^2/2Ns\delta}$$

where

$M(u)$	modularization function;
u	number of NTF components;
N	total number of components;
s	substitutability factor;
δ	degree of coupling.

The term "NTF components" stands for New-To-Firm components. They are the product specific components that are not in the firm's library of components previously.

$$\delta_i = \frac{\text{total number of interfaces in subsystem } i}{\text{number of components in subsystem } i} = \frac{\sum k_c}{n_c}$$

$$\delta_{\text{subsystem}} = \delta_{\text{average}} = \frac{\sum_{i=1}^{I} \delta_i}{I}$$

$$I = \text{ number of subsystems.}$$

$$s = \frac{\text{no. of product families}}{k_{\text{NTF}} \text{ (avg)}} = \frac{\sum_{j=1}^{L} PF_j}{\frac{\sum_{i=1}^{K} k_{\text{NTF}}}{K}}$$

where

L number of product families;

K total number of interfaces of NTF components.

2.4 Customer Order Decoupling Point

After the quality concept has been fully understood by the managers and companies learned how to implement and replicate the quality management systems, competing just on cost is not enough for surviving on volatile markets. Today's unsteady market environment underlines the importance of time-based competition and customization. Time-base competition stresses the importance of operations management, production flow and positioning buffers (Wikner and Rudberg 2005). Furthermore, providing unique components in a very short lead time is critical for the success of customization strategy. In order to respond the demands on time, some of the activities should be performed before receiving customer orders. Customer order-related supply chain activities should be placed downstream and performed after the order is received. This point of separation yielded the idea of customer order decoupling point.

In this section, we will first give the definition as usual. Then, we will stress the importance of the position of the CODP.

2.4.1 Definition

Customer order decoupling point (CODP), also known as order penetration point, is defined by Olhager (2003) as the point where the product is linked to a specific customer order in the manufacturing value chain. He remarks that the different positions of customer order decoupling point specifies the different manufacturing situations such as engineer to order (ETO), make to order (MTO), assemble to order (ATO) and make to stock (MTS). Rudberg and Wikner (2004) also emphasize the relationship between the position of CODP and the manufacturing types (or product delivery strategy). They indicate the following figure:

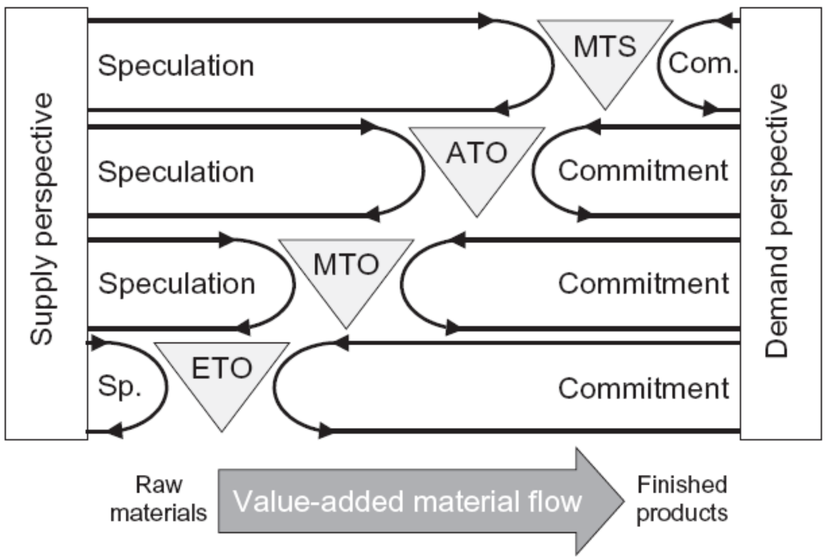

Figure 2-6: The typical sequential approach to the CODP concept (extracted from Rudberg & Wikner 2004)

Rudberg and Wikner (2004) define CODP as the point that separates the decisions made under certainty from decisions made under uncertainty concerning customer demand. In Figure 2-6, the speculation part points out the forecast-driven activities that are done under uncertainty concerning customer demand. On the other hand, the commitment part points out the customer-order-driven activities. Therefore, the triangles between speculation and commitment specify the position of CODP in the value added material flow.

The difference between Olhager's definition (2003) and Rudberg and Wikner's definition (2004) is that while Olhager is emphasizing the place where the order and the specific order product meet, Rudberg and Wikner (2004) identify it as the point where the activities done with anticipation of the order and the activities done with certainty of the order intersect. Sharman (1984) introduce the CODP in a logistics context; he proposes another definition that stresses the product specifications and inventory. He defines the CODP (or OPP) as the point where product specifications typically get frozen, and as the last point which inventory is held (Olhager 2003). One other definition is given by Hoekstra and Romme (1992): "*The decoupling point is the point that indicates how deeply the customer order penetrates into the goods flow*".

Wikner and Rudberg (2005) state that whichever definition is used, the concept of CODP is found on the P:D (P divided by D) ratio, which is presented by Shingo (1981). P stands for the production lead time and D stands for the delivery lead time: what the customer demands and what the company offers. The ratio P:D is important because it expresses the necessary planning and production activities that should be based on speculation (Wikner and Rudberg 2005) (Figure 2-7).

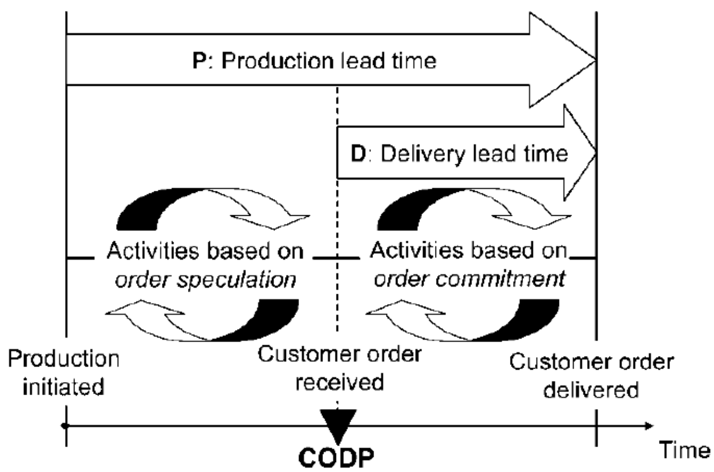

Figure 2-7: The concept of P:D ratio (Wikner and Rudberg 2005)

Wikner and Rudberg (2005) propose the following manufacturing strategy for the corresponding measurement of P:D ratio.

- P/D >> 1 → MTS
- P/D > 1 → ATO
- P/D = 1 →MTO
- P/D < 1 → ETO

It means that if the production lead time is equal to the delivery lead time the customer demands, make-to-order is the appropriate strategy. In order to be able to design the products according to customer orders, delivery lead time should be greater than production lead time. When the delivery lead time demanded by the customer is short, the appropriate strategy is ATO; if it is shorter, then the products should be finalized in advance and kept in stock.

2.4.2 Positioning the CODP

Rudberg and Wikner (2004) state that the position of CODP depends on the balance of two counteracting forces: productivity force and flexibility force. When the cost is the major competitive priority, productivity force pushes the position of the CODP downstream. On the other hand, when flexibility and specific customer requirements are the subject, flexibility forces pushes the position of CODP upstream. They illustrate their ideas in Figure 2-8.

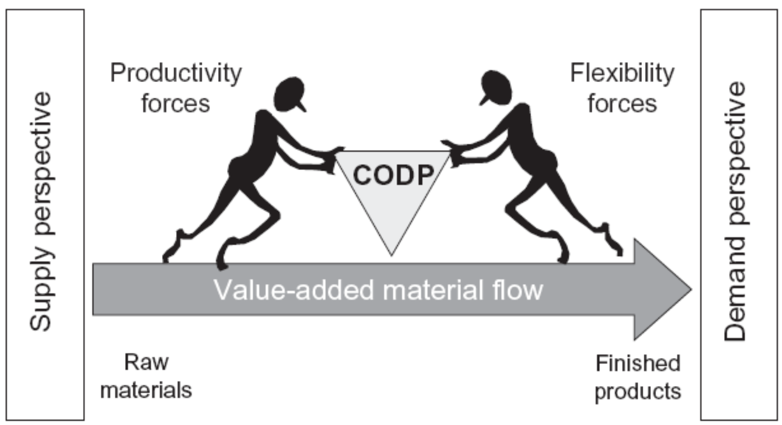

Figure 2-8: The productivity-flexibility tradeoff and the positioning of the CODP (Rudberg and Wikner 2004)

Olhager (2003) investigates the factors affecting the position of the CODP. He groups the factors into three categories: market-related factors, product-related factors, and production-related factors.

Olhager (2003) proposes delivery lead time, product demand volatility, product volume, product range & product customization requirements, customer order size & frequency and seasonal demand as market related factors. He states that market limits how far backwards the COPD can be placed with respect to delivery lead time. If the product demand volatility is low, it is easier to forecast the demand and position the CODP to an upstream position. It is also stated that high volume demanded creates the same effect as low volatility. Product range & customization requirements push the CODP upstream as Rudberg and Wikner (2004) also stated (flexibility force). Seasonality causes shifts in CODP interchanges of manufacturing strategy among MTS and MTO or ATO (Olhager 2003).

Modular product design, customization opportunities, material profile and product structure are the product-related factors that affect the position of CODP (Olhager 2003). In general, modular product design requires efficiency in upstream operations and short delivery lead time, which indicates ATO as appropriate. If the customization penetrates early in the manufacturing stage, MTO policy is necessary; otherwise ATO can be appropriate. The number of items at various levels of the product structure constitutes the material profile, which indicates the position of the CODP (Olhager 2003). Depth and breadth of the product structure, which indicates the product complexity, is related to production lead time; and P:D ratio defines the position of the CODP as previously mentioned (Olhager 2003, Rudberg and Wikner 2004)

Production-related factors proposed by Olhager (2003) are production lead time, planning points, flexibility, bottleneck and sequence-dependent set-up times. Production lead time is a major factor with required delivery lead time (P:D ratio). High product variety and customization, previously mentioned, can be achieved by the flexibility of the production processes. In addition, flexibility is also required for make to order policy. The bottleneck should be placed upstream the CODP when demand volatility and product variety should not meet bottleneck. Conversely, it should be placed downstream when the waste elimination is critical for the production (Olhager 2003). And finally, resources with sequence-dependent set-up times should be placed upstream not to turn them into a bottleneck (Olhager 2003).

According to the factors previously mentioned, Olhager (2003) represents the following model to show the interactions among them. (Figure 2-9)

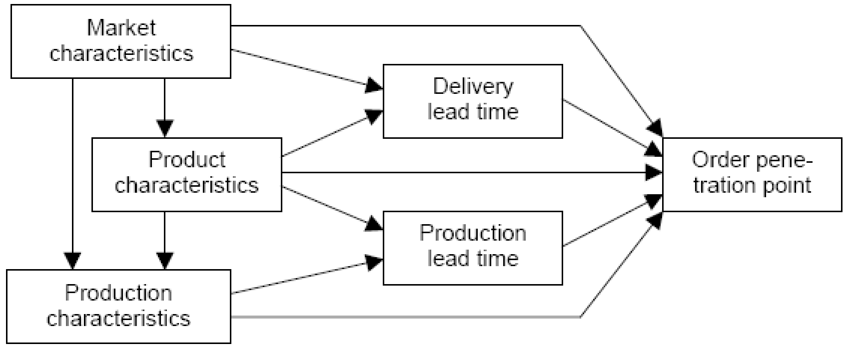

Figure 2-9: Conceptual impact model for factors affecting the positioning of the CODP (extracted from Olhager 2003)

Olhager (2003) states that any change in the COPD needs to be strategically motivated, like strengthening a competitive priority. He puts forward two driving forces to move CODP downstream (forward): reduce delivery lead time to customers and increase the manufacturing efficiency. He also states that increasing the knowledge of the contents of customer orders at the time of production is the main force to move CODP upstream (backward). Olhager (2003) summarizes the competitive advantages, reasons and negative effects of shifting the CODP forward or backward in the following figure. (Figure 2-10)

	Competitive advantage addressed	*Reasons for forward shifting*	*Negative effects*
Forward shifting	Delivery speed Delivery reliability Price	Reduce the customer lead time Process optimisation (improved manufacturing efficiency)	Rely more on forecasts (risk of obsolescence) Reduce product customisation (to maintain WIP and inventories levels) Increase work-in-process (due to more items being forecast-driven)

	Competitive advantage addressed	*Reasons for backward shifting*	*Negative effects*
Backward shifting	Product range Product mix flexibility Quality	Increasing the degree of product customisation Reduce the reliance on forecasts Reduce or eliminate WIP buffers Reduce the risk of obsolescence of inventories	Longer delivery lead times and reduced delivery reliability (if production lead times are not reduced) Reduced manufacturing efficiency (due to reduced possibilities to process optimisation)

Figure 2-10. Strategic issues, reasons and negative effects of shifting the CODP (Olhager 2003)

3. Relationships of Concepts

In Chapter 3, we will state how these four concepts (mass customization, postponement, CODP and modularization) are related to each other. The aim of this chapter is to build the basic blocks that are necessary for our model. The method used to investigate the relationships is to research the literature (articles, books, case studies, empirical analysis…).

3.1 Mass Customization and Modularization

The literature about the relationship between mass customization and modularization is well-developed. Kumar (2004) has contributed the literature with an important study of relationship. He states that "*all companies with marketing multi-feature, multi-functional products would necessarily have to have modularity to achieve economies of scale*". However, he gives some examples of mass customization where modularity is not required. For example, TC^2, which is a customized jeans producer, scans the customers' body measurements with advance optical technology in a few seconds and sends the data to manufacturing unit instantly. In manufacturing unit, laser guns of cutting machines shape the jeans in an hour. Customized jeans without any modularity reach the customers in 3 to 5 days with an extra cost of 15 dollars. Another example is Custom Foot, footwear producers. Custom Foot works with the same logic of TC^2 to produce customized shoes. These companies have achieved nearly zero set-up time and zero set-up cost, so the economies of scale is not an important factor (Kumar 2004). Kumar (2004) states that except for this kind of unique customizers and companies in early stage of mass customization, modularity is essential for mass customization.

One well-known example of mass customization through modularization is from HP printers. Feitzinger and Lee (1997) describe how HP achieved mass customization. They state that differentiating a product for a specific customer as late as possible in the supply network is the answer of how to achieve an effective mass customization. Instead of finalizing HP DeskJet printers in the main manufacturing plant in Singapore, they are sent to local distribution centers (for Europe, in Stuttgart) to be customized. Country-specific power supply and manuals are added to the product and the printers are packaged in distribution centers. Although manufacturing cost is a little bit higher than finishing products in central manufacturing unit, total cost (manufacturing + distribution + inventory) decreased by 25%.

They propose three organizational-design principles for the success of an effective mass customization program:

- Products should be composed of independent modules in order to be assembled easily and inexpensively.
- The idea of independent modules should be used also in the design of manufacturing processes, so that processes can be easily moved or rearranged for different distribution-network design.
- While the supply network is providing the basic products to customization facilities in a cost-effective manner, it must also have the flexibility and the responsiveness to take individual customers' orders and deliver the finished, customized goods quickly. (Feitzinger & Lee 1997)

The first two of these principles point out the relationship between modularization and mass customization explicitly. The last one emphasizes the leagility concept in mass customization, which we will define and explain in section 3.3 Mass Customization and Postponement.

Kumar (2004) states that the cost efficiencies are being obtained through modular product design in mass customization and he adds that modularity in the basic product or service design is essential for mass customization (Pine 1993, Pine et al., 1993, Duray 2002, Tu et al. 2004). He illustrates how modularity works to provide mass customization (Figure 3-1). He identifies seven steps:

> "Step 1: Customer co-designs/configures his/her choice product by picking up levels/options for each feature/function available to him/her within the finite solution space.
>
> Step 2: A mapping mechanism identifies and selects from a list all the product modules/ components that will be needed to make the configured product.

Step 3: Stable and flexible processes are chosen that will fabricate the modules identified in Step 2. This is where modular/cellular processes (one process dedicated to one module) are helpful.

Step 4: A dynamic process is developed connecting the above processes in an appropriate sequence.

Step 5: A schedule is generated so that each process is triggered when there are enough modules for each process so as to allow the advantage of economies of scale.

Step 6: All modules are assembled at the last stage.

Step 7: Customized/pre-configured product is delivered to the customer." (Kumar 2004)

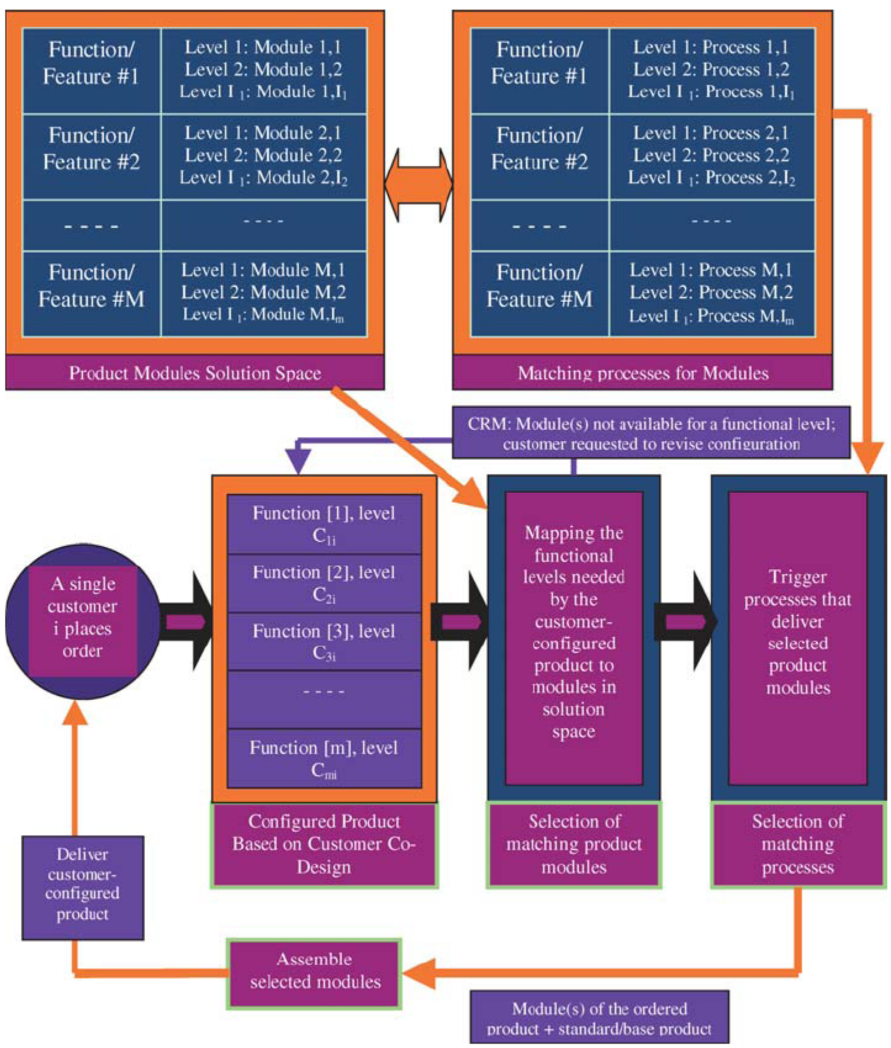

Figure 3-1: Mass Customization through Modularity (Kumar 2004)

Mikkola (2007) investigates the implications of modularity for mass customization by using the "modularization function", self-designed. A brief explanation of this function is mentioned in the modularity section. She proposed a new model to measure the mass customization opportunity depending on the modularization function.

$$MC[M(u)] = me^{-u^2/2Ns\delta} \quad 0.0 \leq m \leq 1.0$$

where *m* shows the degree of product variety present in a given product architecture, and calculated by the following formulas.

$$m = \frac{k_1 n_{\text{STD-NON-CUST}} + k_2 n_{\text{STD-CUST}} + k_3 u_{\text{NON-CUST}} + k_4 u_{\text{CUST}}}{N};$$
$$0.0 \leq k_1, k_2, k_3, k_4 \leq 1.0$$
$$N = n_{\text{STD-NON-CUST}} + n_{\text{STD-CUST}} + u_{\text{NON-CUST}} + u_{\text{CUST}}$$
$$k_1 = \frac{n_{\text{STD-NON-CUST}}}{\sum n_{\text{STD-NON-CUST}} \text{ (from aggregate MPS)}} \quad k_2 = \frac{n_{\text{STD-CUST}}}{\sum n_{\text{STD-CUST}} \text{ (from aggregate MPS)}}$$
$$k_3 = \frac{u_{\text{NON-CUST}}}{\sum u_{\text{NON-CUST}} \text{ (from aggregate MPS)}} \quad k_4 = \frac{u_{\text{CUST}}}{\sum u_{\text{CUST}} \text{ (from aggregate MPS)}}$$

$n_{\text{STD-NON-CUST}}$	number of noncustomizable standard components;
$n_{\text{STD-CUST}}$	number of customizable standard components;
$u_{\text{NON-CUST}}$	number of noncustomizable unique components;
u_{CUST}	number of customizable unique components;

By using these formulas, Mikkola (2007) proposes four important modular product principles for mass customization.

1. Utilization of unique components (components that are new-to-firm and product-specific) should be minimized (lowering *u*).
2. Level of product architecture decomposition (δ) should be maximized. In other word, interaction of components in a module should be high.
3. Unique components should be tried to use in as many product families as possible (increasing *s*).
4. Utilization of standard components in other products should be maximized (increasing *m*).

Mikkola (2007) illustrates her ideas in the following figure that shows how modularization function works for mass customization. Negative signs stand for the negative effect of the factor on modularity and indirectly on mass customization; positive signs show the positive effect (Figure 3-2).

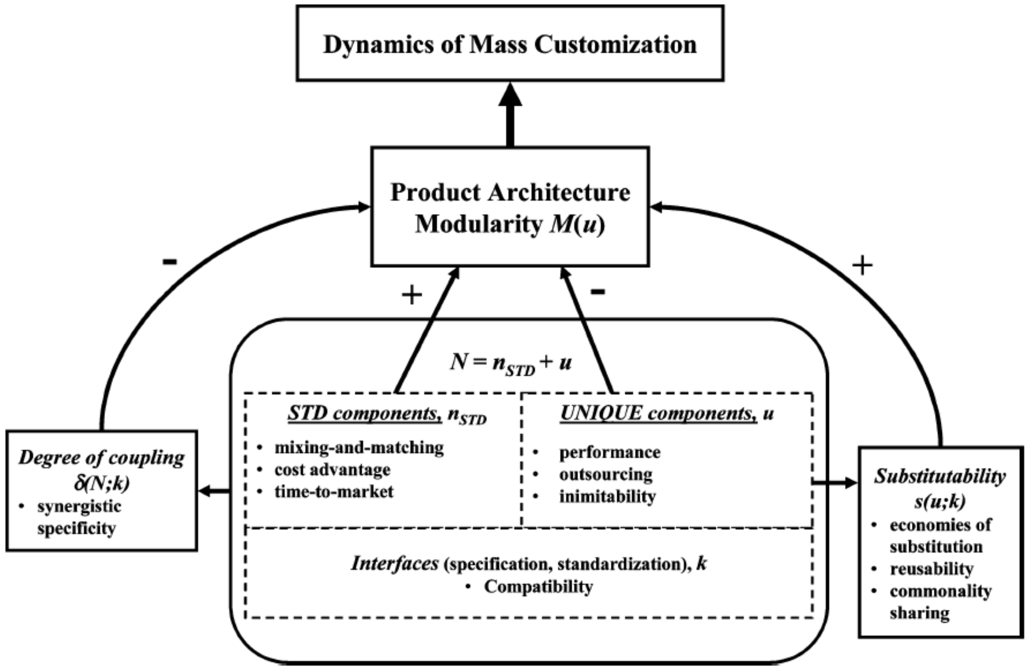

Figure 3-2: Mass customization through the application of MF (adopted from Mikkola 2007)

We can summarize the relationship of mass customization and modularization as shown in Table 3-1.

Relationship	Authors	Theory
Mass customization & Modularization	Feitzinger & Lee (1997)	Modularity in product design and manufacturing processes is necessary for the success of mass customization.
	Kumar (2004)	Modularization works to provide mass customization and this is explained by a step-by-step methodology.
		The cost efficiencies are being obtained through modular product design in mass customization. And Modularization is essential for mass customization.
	Mikkola (2007)	Mass customization can be measured as a function of modularity.

Table 3-1: The relationship of mass customization and modularization

3.2 Postponement and Customer Order Decoupling Point

The main reason to postpone some of the operations is the absence of customer order information. As we mentioned in the "postponement as a tool of uncertainty management" section, in order to provide efficiency, some operations requiring information about customer order should be moved downstream and in exchange some operations that do not require customer order information or can be done in anticipation should be moved upstream. Otherwise, the company has to cope with high work in progress inventory and long lead times and consequently material flow may stop. The point in which the customer order penetrates the system is CODP, as defined before. It is the point that the missing information causing postponement of operations is held. So, the relationship between CODP and postponement is tight.

One of the important studies about the relationship of postponement and CODP is conducted by Yang and Burns (2003). While we were describing postponement concept individually, we have placed their model that indicates postponement strategies corresponding to the location of CODP. It is useful to mention again this model at this point (Figure 2-1 and Figure 3-3).

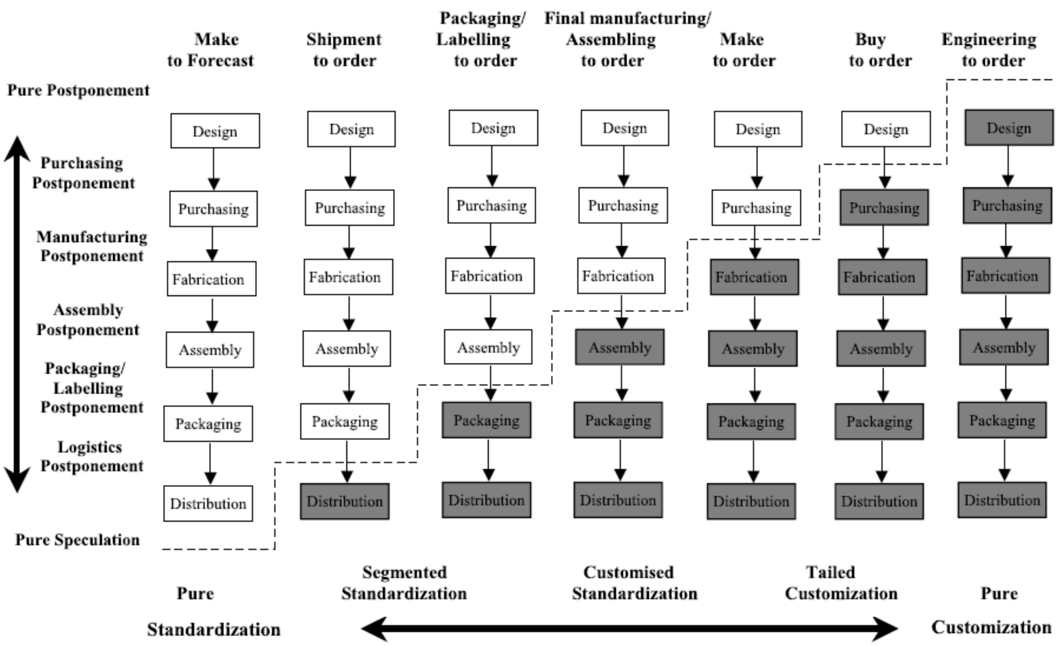

Figure 3-3: Speculation-postponement strategy and a continuum of standardization-customization (adapted from Yang & Burns 2003)

They state that the dotted line in Figure 3-3 indicates the location of CODP. From left to right, the depth of postponement increases and the CODP gets further away from the end user. In order to remove any misunderstanding, it is necessary to emphasize that postponement does not cause CODP to be further away from end user. It is actually the opposite. The truth is “*postponement is used to move the decoupling point (CODP) closer to the end user and increase the efficiency and effectiveness of the supply chain”* (Yang & Burns 2003). We can illustrate this by the example of HP DeskJet printers (Figure 3-4).

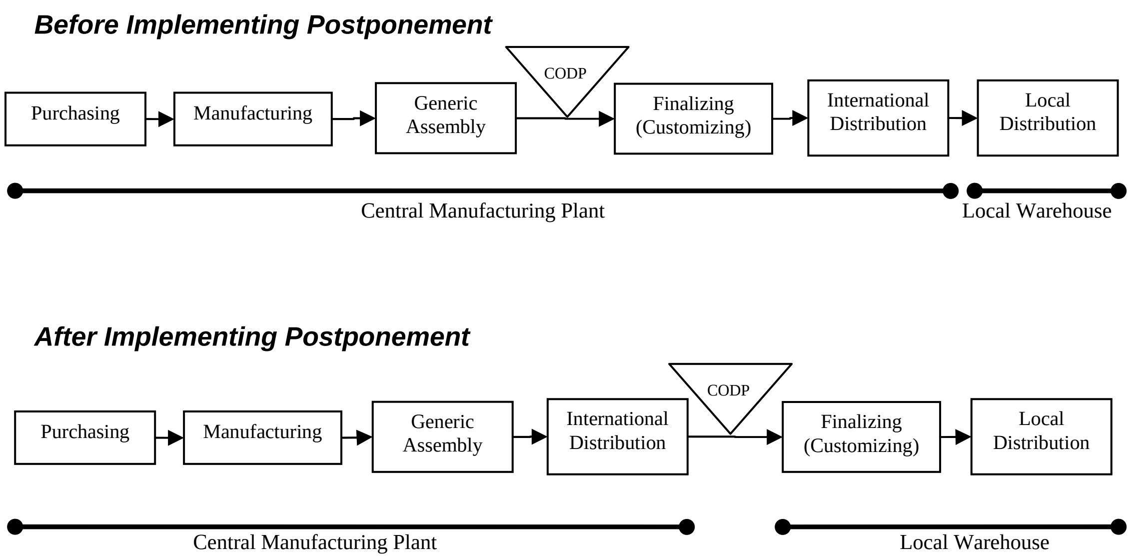

Figure 3-4: Comparison of material flows of HP DeskJet printers before and after postponement implementation

By moving customization operations from central manufacturing plant to local warehouses, location of the CODP shifts to downstream, closer to end-user. Consequently, both efficiency and responsiveness increase in the supply chain. The main benefit hides behind moving international distribution, which is not related with customization, to upstream and finalizing products, which is related with customization, to downstream.

Yang and Burns (2003) state that in order to position the CODP, companies may start with postponement application. They propose that customer-order-information related activities should be postponed behind the CODP. They ask four questions to rearrange the steps along the supply chain: Are all existing processes behind the CODP closely associated with the customer order? If not, can they possibly be moved before the CODP? Are all existing processes before the CODP not associated with the customer order at all? If yes, can they possibly be moved after the CODP? (Yang & Burns 2003)

Feitzinger and Lee (1997) give the example of Benetton to indicate the importance of re-sequencing the manufacturing sub-processes for postponement. Yang and Burn (2003) investigate the same example from CODP and postponement point of view. At the beginning, Benetton was dyeing the purchased yarn according to the customer-order and future order anticipation. Then, colored yarn was transformed to garment parts and these parts were knitted. As a result of this system, some of the color garments became obsolete and garments with colors in demand were sold out. Benetton postponed the dying operation and shifted CODP downstream by re-sequencing the manufacturing sub-processes. Through this new process, knitted garments are colored according to the customer order, as a result, obsolescence risk and sold-out risk is removed. The old manufacturing process and new manufacturing process is compared in Figure 3-5.

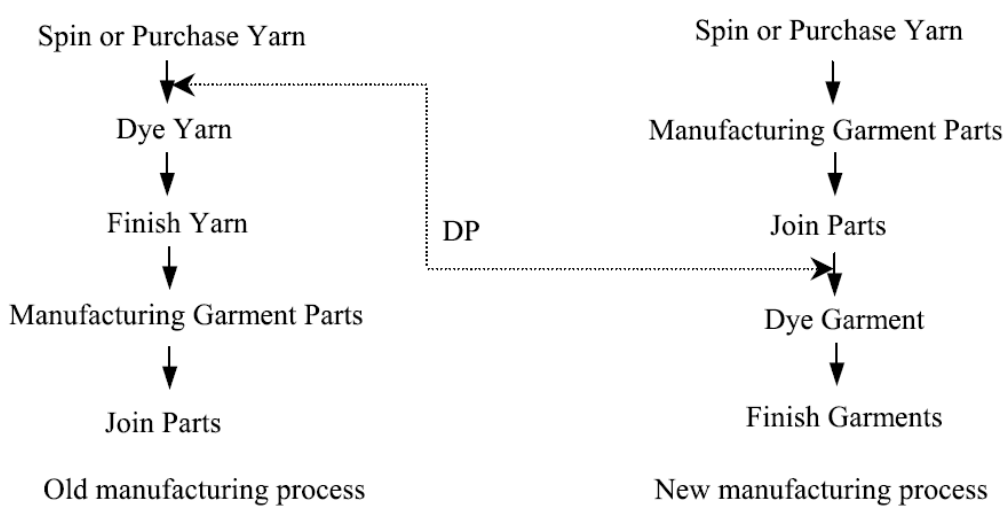

Figure 3-5: Postponement application in Benetton (Yang & Burns 2003)

We can briefly show the relationship of postponement and CODP in Table 3-2.

Relationship	**Authors**	**Theory**
Postponement & CODP	Yang and Burns (2003)	Postponement is used to move the CODP closer to the end user and increase the efficiency and effectiveness of the supply chain.

Table 3-2: The relationship of postponement and CODP

3.3 Mass Customization and Postponement

Feitzinger and Lee (1997) state a key sentence that explains the relationship of mass customization and postponement: "*The key to mass-customizing effectively is postponing the task of differentiating a product for a specific customer until the latest possible point in the supply network (a company's supply, manufacturing, and distribution chain)*". They also state that in order to increase efficiency and responsiveness, companies must integrate product designs, manufacturing and logistics processes and supply network. Therefore, delayed differentiation for mass customization requires appropriate product design, processes and supply network.

The relationship between mass customization and postponement can be better understood by the concept of leagility. Leagility is defined as: combination of the lean and agile paradigm within a total supply chain strategy by positioning the decoupling point so as to best suit the need for responding to a volatile demand downstream yet providing level scheduling upstream from the decoupling point (Naylor et al. 1997 – according to Mason-Jones et al. 2000). Mason-Jones et al. (2000) illustrate the leagility concept in Figure 3-6.

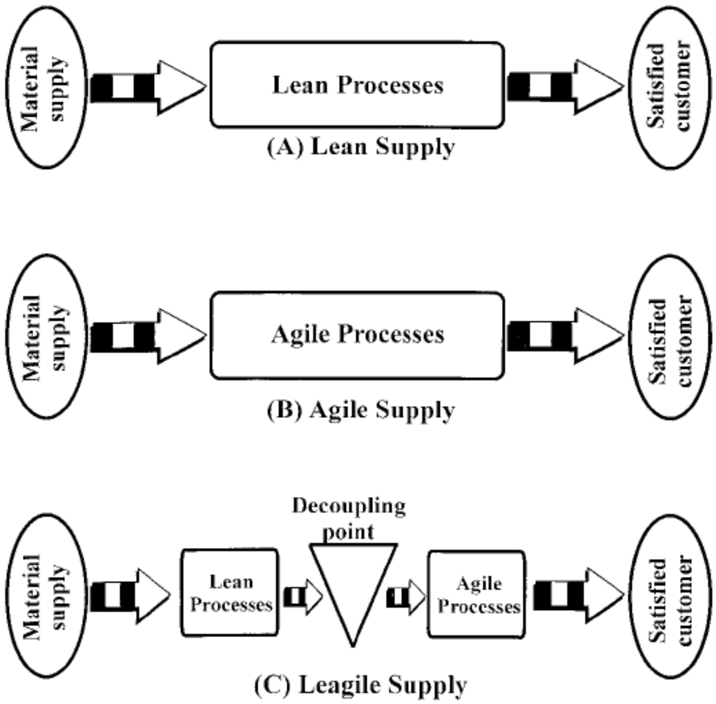

Figure 3-6: Lean, agile and leagile supply (Mason-Jones et al. 2000)

As we previously defined, mass customization naturally indicates a leagile supply chain, because it states the importance of both efficiency and responsiveness. It is basically producing customized products efficiently like mass production. The lean part of leagile supply shows the "mass" part of mass customization and the agile part of leagile supply shows the "customization" part of the mass customization.

For postponement, authors have different point of views. Yang et al. (2004a) state that postponement has been identified as an important approach for contributing to the attainment of agility, e.g. through its contribution to the customization of products and services; use of customer order information through the supply chain; and cross functional efforts (Van Hoek 2000). In the same article, it is claimed that postponement is crucial for any agile strategy according to Christopher (2000). On the other hand, Yang and Burns (2003) claim that postponement works for moving CODP downstream, consequently increases the efficiency and effectiveness of the supply chain. Therefore, we can say that postponement is seen as a concept which contributes both efficiency (lean) and responsiveness (agile).

Van Hoek (2000) proposes a combined view of efficiency and responsiveness; he states that leagility should be targeted at an operational level for the implementation of postponement. Van Hoek (2000) illustrates this idea in Figure 3-7.

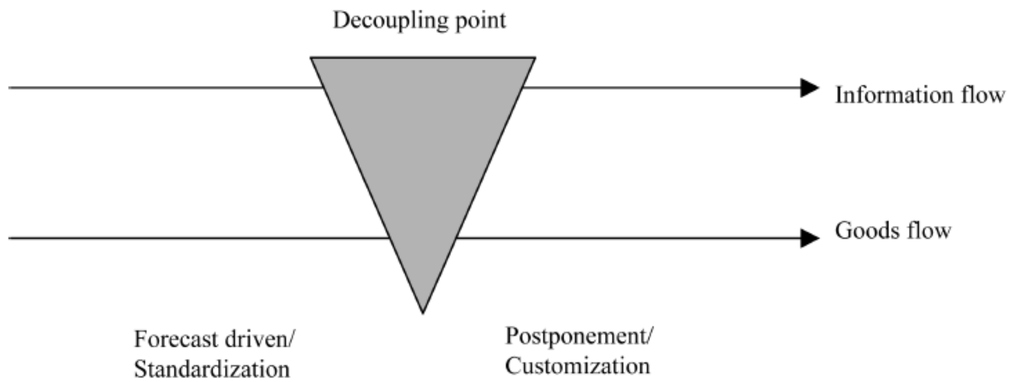

Figure 3-7: Leagility (Van Hoek 2000)

The relationship of mass customization and postponement can be analyzed under the term of leagility. We state that mass customization, naturally, requires a leagile supply chain because both efficiency and responsiveness are two important principles for the success of the mass customization strategy. And also, we state that postponement contributes both to efficiency and to responsiveness. Therefore, we can propose that postponement contributes to the leagile supply chain of mass customization.

Relationship	**Authors**	**Theory**
Mass customization & postponement	Feitzinger and Lee (1997)	The key to mass customizing effectively is postponing the task of differentiating a product for a specific customer until the latest possible point in the supply network.
	Yang et al. (2004) & Christopher (2000)	Postponement has been identified as an important approach for contributing to the attainment of agility, e.g. through its contribution to the customization of products and services.
	Van Hoek (2000)	Leagility should be targeted at an operational level for the implementation of postponement.

Table 3-3: The relationship of mass customization and postponement

3.4 Mass Customization and Customer Order Decoupling Point

Rudberg and Wikner (2004) published a significant piece for the relationship of mass customization and CODP. They first mention the productivity – flexibility tradeoff while positioning CODP. Then, they explain the concepts individually. CODP is studied in two dimensions (engineering dimension and production dimension) in order to analysis customer involvement in mass customization. Order promising in mass customization is explained next with a general model. In this part of our thesis, we will use Rudberg and Wikner's (2004) research.

Rudberg and Wikner (2004) state that the positioning of the CODP in mass customization involves identifying the optimal balance between the productivity and flexibility forces. When CODP is moved upstream in the material flow, flexibility is underlined as a competitive priority and the customization ability of manufacturing system increases. On the other hand, when we move CODP downstream, productivity is emphasized and company can better compete by price. For positioning CODP, it should be considered that the marginal benefit from flexibility decreases while CODP is moved more upstream and the marginal benefit from productivity decreases while CODP is moved more downstream (Rudberg and Wikner 2004). Therefore Rudberg and Wikner (2004) state that a balance between these forces is necessary for achieving mass customization.

Rudberg and Wikner (2004) propose a two-dimensional approach for the analysis of CODP. First dimension, the production dimension reflects the traditional point of CODP view. $CODP_{PD}$ is the point where forecast-driven manufacturing operations and customer-order-driven manufacturing operations are separated. Second dimension is the engineering dimension. According to this dimension, forecast-driven product engineering and design is separated from order-driven engineering and design by $CODP_{ED}$. MTO_{ED} stands for order-driven design, MTS_{ED} stands for forecast-driven design. Between these two, ATO_{ED} is placed, which stands for adopt-to-order. They illustrate two dimensional CODP in Figure 3-8.

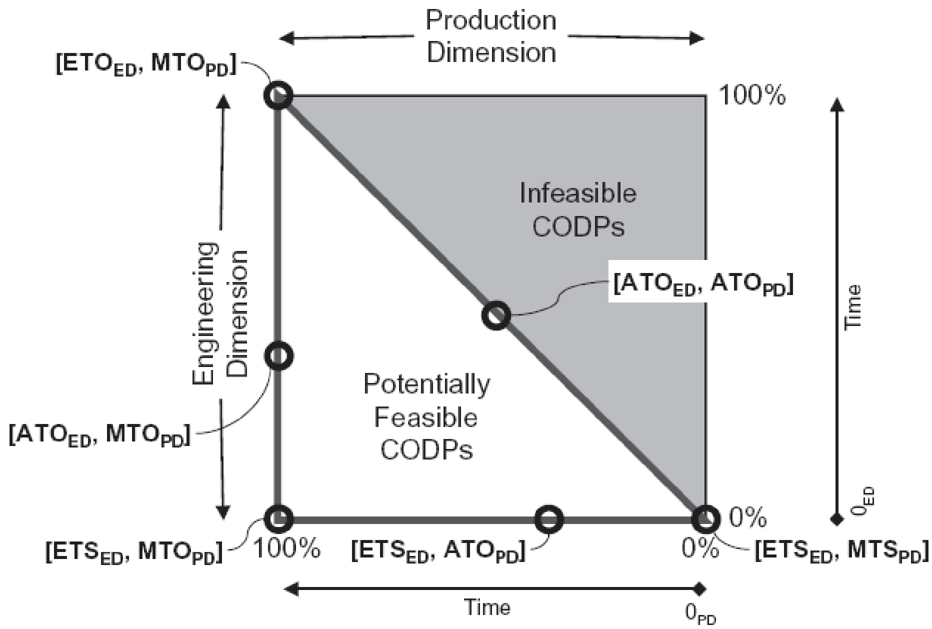

Figure 3-8: The two-dimensional CODP space (Rudberg and Wikner 2004)

Rudberg and Wikner (2004) also investigate order promising in mass customization according to the two-dimensional CODP. They state that for each dimension of CODP, there are two main kinds of constraints that affect the accuracy of the order promise. First one is the material constraint which is related to the raw materials, modules and finished parts for the production dimension and existing engineering designs for the engineering dimension. In production planning and control terminology, these buffers are called *available-to-promise* (ATP), materials (or designs) which are not allocated to a specific order yet (Rudberg & Wikner 2004). The second one is the capacity constraint which is related to resources like machines, computers or humans. It is labeled as *capable-to-promise* (CTP), which is the more comprehensive form of ATP by considering resources. Rudberg and Wikner (2004) state that order confirmation process in a mass customization system requires both ATP and CTP functionality in engineering and production dimensions separately.

They propose a general model which is the union of engineering and production dimensions (Figure 3-9). According to this model, the position of CODP specifies which of the ATP and CTP functionalities works. For example, if the CODPs of production and engineering dimensions are located far upstream ([ETO_{ED}, MTO_{PD}]), required lead time for production and engineering is determined by CTP_{ED} and CTP_{PD}. Similarly, if the CODPs are located far downstream, another extreme, order promising process will work dependent to ATPs. For the CODP positions between these two extreme, appropriate functionality of order promising can be seen in Table 3-4.

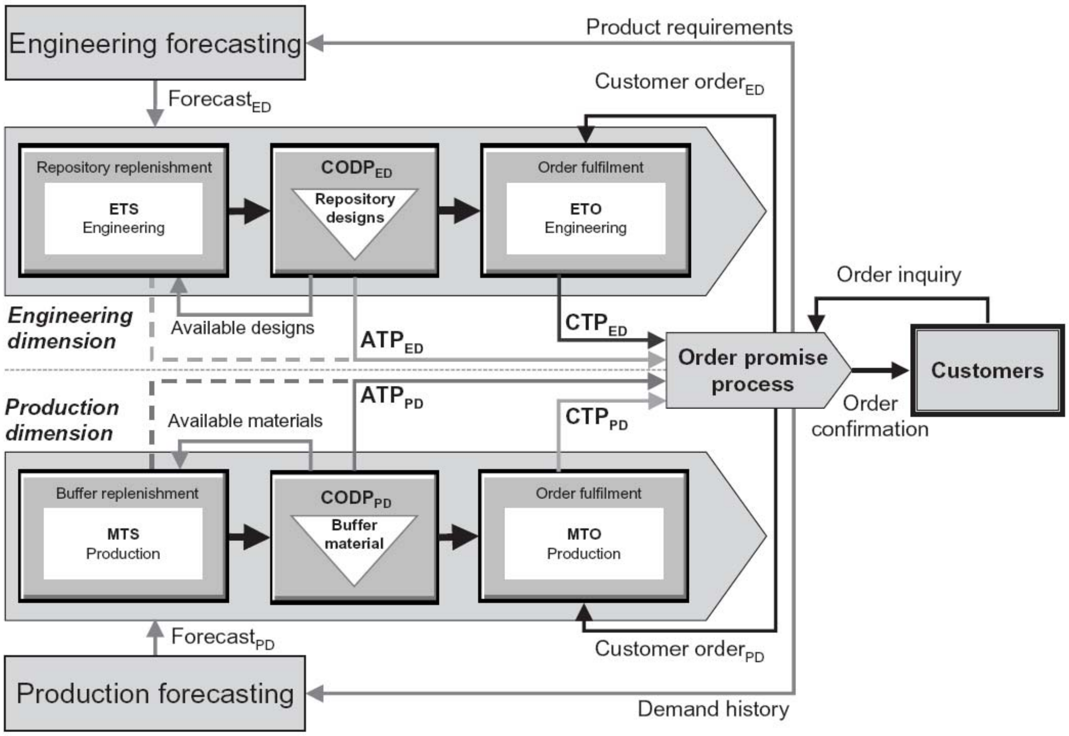

Figure 3-9: A general model of the order-promise process for mass customization environments (Rudberg & Wikner 2004)

CODP tuple	Traditional CODP	Order promise based upon			
		Engineering		Production	
[ETO_{ED}, MTO_{PD}]	ETO	–	CTP_{ED}	–	CTP_{PD}
[ATO_{ED}, MTO_{PD}]	–	ATP_{ED}	CTP_{ED}	–	CTP_{PD}
[ATO_{ED}, ATO_{PD}]	–	ATP_{ED}	CTP_{ED}	ATP_{PD}	CTP_{PD}
[ETS_{ED}, MTO_{PD}]	MTO	ATP_{ED}	–	–	CTP_{PD}
[ETS_{ED}, ATO_{PD}]	ATO	ATP_{ED}	–	ATP_{PD}	CTP_{PD}
[ETS_{ED}, MTS_{PD}]	MTS	ATP_{ED}	–	ATP_{PD}	–

Table 3-4: The CODP typology and the order-promising process (Rudberg & Wikner 2004)

Finally, Rudberg and Wikner (2004) emphasize the importance of specifying the initial customer involvement for the degree of customizing. They state that degree of customization should be relevant to customer requirements and existing capabilities while locating the initial customer involvement.

Following table (Table 3-5) explains the relationship of CODP and mass customization briefly.

<table>
<tr><th>Relationship</th><th>Authors</th><th>Theory</th></tr>
<tr><td rowspan="2">Mass customization & CODP</td><td rowspan="2">Rudberg and Wikner (2004)</td><td>Positioning of the CODP in mass customization involves identifying the optimal balance between the productivity and flexibility forces.</td></tr>
<tr><td>Degree of customization should be relevant to customer requirements and existing capabilities while locating the initial customer involvement.</td></tr>
</table>

Table 3-5: The relationship of mass customization and CODP

3.5 Postponement and Modularization

While explaining how HP enabled mass customization, Feitzinger and Lee (1997) put forward the relationship of postponement and modularization. As we previously mentioned, they emphasize the importance of two forms of modularity and agile supply chain for an effective mass customization program. In this part of the study, we will stress these two forms of modularity and why they are necessary for postponement.

Yang et al. (2004a) define the two forms of modularity:

1. ***Modularity in design*** *refers to defining the design boundaries of a product and of its components so that design features and tasks avoid creating strong interdependencies among specific components (modules) design (Baldwin and Clark 1997). A fully modular architecture means that a change made to one component does not require a change to other components (Ulrich 1995).*

2. ***Modularity in production*** *refers to designing the production process in order to make complicated products by designing and developing modules at different sites and then bringing them together to create a complete system (Baldwin and Clark 1997). This modularity breaks down the whole production process into sub-processes that can be performed concurrently or in a different sequential order (Lee 1998).*

According to the Fine (1998), performing some parts of the processes at a different time or location increases the process modularity because of the geographical distance, ownership separation and different cultural features (Yang et al. 2004a). In addition, in order to be able to delay some part of the processes, it is obvious that the processes should be able to be broken down into smaller sub-processes by modularity (Lee 1998). Therefore, we can say that modularity in processes (like manufacturing process) is a prerequisite for postponement (Yang et al. 2004a, Feitzinger & Lee 1997)

Feitzinger and Lee (1997) exemplify the importance of modular process design for postponement with paint manufacturers. Paint manufacturers produce generic paint and a variety of color pigments which are mixed according to the customer specific order at the hardware and paint stores. Stores use a chromatograph which analyzes customers' paint samples and to determine paint and pigment mixture that will match it. By doing so, paint manufacturers and paint stores do not have to stock many different colors; and virtually they serve unlimited number of color options. The key to postponement was separating the paint production into two sub-processes (the production of the paint and the mixing of the pigment and paint) and creating a low-cost chromatograph (Feitzinger & Lee 1997). This confirms that modularity in process is necessary for the postponement.

Van Hoek (2001) also investigates the relationship of postponement and modularization. He states that in electronics and automotive industries, modular product design allows for postponement in manufacturing; but in process industries such as pharmaceuticals, postponement may mean to fully redesign the processes by focusing on commonality and modularity as design principles in order to be able to decouple the manufacturing processes.

Van Hoek (2001) stresses two impact of modularity on postponement. The first one is that modularity enables rapid final manufacturing at low processing costs and increases the possibility to adjust products to markets. This is because assembling the generic modules according to customer order takes less time and is more cost-efficient compared to fabricating customer-ordered products. The second one is that high commonality of modules lowers inventory levels and reduces the risk of obsolete inventories. This is due to the pooling effect of the inventories. When modules are used for more than one product or product family compared to using different modules for those, the possible demand for the modules increases; and consequently, the obsolescence risk associated with the modules decreases. Therefore, modularity in processes is necessary for postponement and modularity in product ease postponement by contributing cost performance and reducing the obsolescence risk.

Relationship	**Authors**	**Theory**
Postponement & Modularization	Yang et al. 2004a, Feitzinger & Lee 1997	Modularity in processes (like manufacturing process) is a prerequisite for postponement.
	Van Hoek (2001)	Modularity enables rapid final manufacturing at low processing costs and increases the possibility to adjust products to markets.
		High commonality of modules lowers the inventory levels and reduces the risk of obsolete inventories.

Table 3-6: The relationship of postponement and modularization

3.6 Customer Order Decoupling Point and Modularization

We have searched the literature for the relationship of CODP and modularization. As far as we investigate, there is not any direct relationship of these two concepts. According to our study, these two concepts are related to each other under the terms of the other two concepts, mass customization and postponement. We have previously mentioned the other combinations of relationships.

In our model, modularization is used to contribute both to customization and to efficiency and it is necessary for the success in some mass customization industries. On the other hand, CODP is used to balance the efficiency and flexibility forces. For postponement, modularization is required (process modularity) and increases the manufacturing (or assembly) and delivery speed (product modularity). And postponement affects the CODP by moving it downstream. Therefore, we can propose that CODP and modularization is not directly related, but they are dependent to each other under the terms of mass customization and postponement.

4. Combined Model

First, we have analyzed the concepts individually. And then, in the previous section we have investigated the pair-wise relationships of concepts. We have built a relationship table at the end of every relationship analysis. In this part of the study, we will try to combine the pair-wise relationships and create a model that explains all the relationships. Later, we will exemplify our model with an illustration figure.

4.1 Table of Relationships

	Postponement	**Modularization**	**CODP**
Mass Customization	The key to mass customizing effectively is postponing the task of differentiating a product for a specific customer until the latest possible point in the supply network. Postponement has been identified as an important approach for contributing to the attainment of agility, e.g. through its contribution to the customization of products and services. Leagility should be targeted at an operational level for the implementation of postponement.	Modularity in product design and manufacturing processes is necessary for the success of mass customization. Modularization works to provide mass customization and this is explained by a step-by-step methodology. The cost efficiencies are being obtained through modular product design in mass customization. And Modularization is essential for mass customization. Mass customization can be measured as a function of modularity.	Positioning of the CODP in mass customization involves identifying the optimal balance between the productivity and flexibility forces. Degree of customization should be relevant to customer requirements and existing capabilities while locating the initial customer involvement.
Postponement		Modularity in processes (like manufacturing process) is a prerequisite for postponement. Modularity enables rapid final manufacturing at low processing costs and increases the possibility to adjust products to markets. High commonality of modules lowers the inventory levels and reduces the risk of obsolete inventories.	Postponement is used to move the CODP closer to the end user and increase the efficiency and effectiveness of the supply chain.

Table 4-1: The relationships of four concepts

In the "relationship of concepts" section, we have investigated the pair-wise relationships. In the following table (Table 4-1), we have assembled the 5 tables (Tables 3-1, 3-2, 3-3, 3-5, 3-6), explained before, together. We think that using one table for the relationships can be beneficial to see the whole picture. Every cell, which is the intersection of the particular row and columns, shows the relationships of concepts indicated by that column and row.

4.2 Model Chart

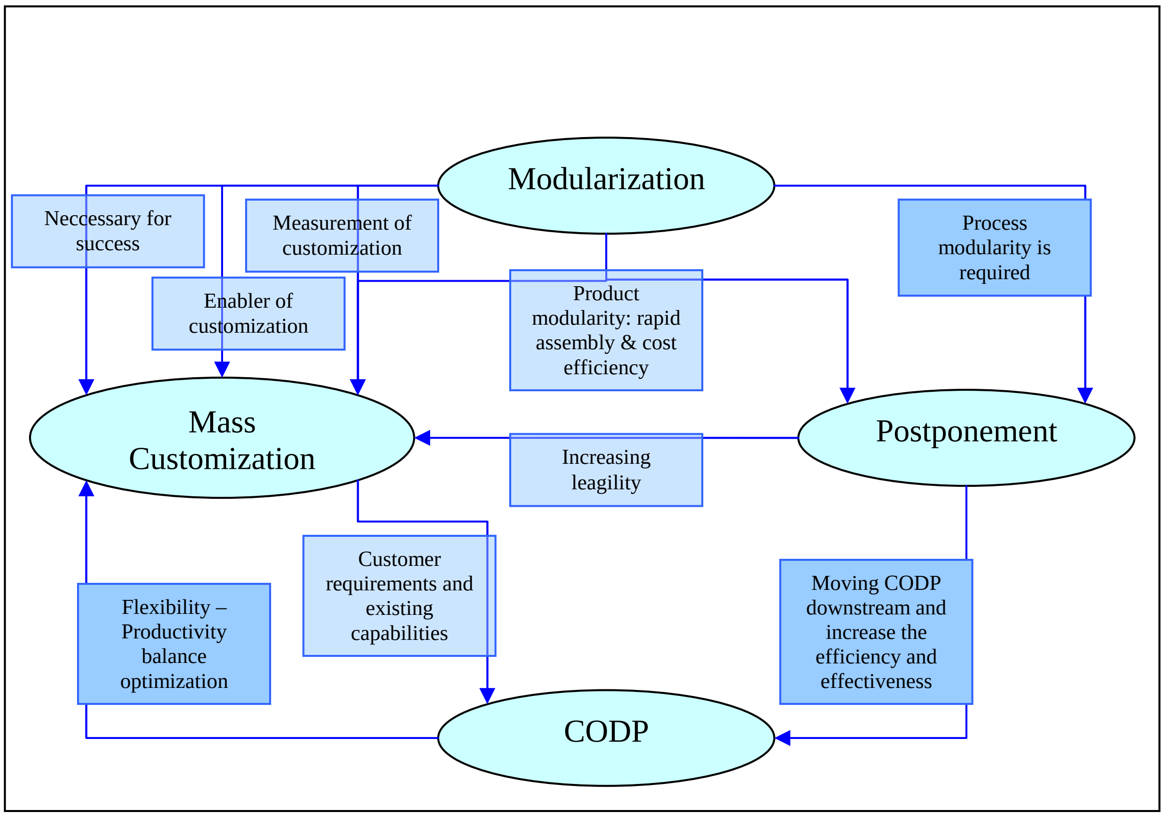

Figure 4-1: Model Chart

We have built the previous chart (Figure 4-1) according to the "relationships of four concepts" table (Table 4-1). It tells how the concepts are affected by each other. In this part of the thesis, we will try to explain this chart.

As we previously mentioned, in some industries modular product design is not always necessary for mass customization. For illustrating this, we have given the example of customized garment manufacturer, TC^2, from Kumar (2004). In TC^2 example, customized garments according to the body measurements of the customers are produced by cutting and sewing as efficiently as mass production without any product modularity. But, this is a unique example, because there is no set-up cost for TC^2 and this makes the benefits of modularization insignificant. Except this unique example and other examples where there is no set-up cost, product modularity is necessary for the success of mass customization in many industries such as electronics and automotive. It enables the customization options, cost efficiency and rapid assembly. Modularity is also used to measure how close a system is to mass customization (MC[MF] – Mikkola 2007).

While we were investigated CODP individually, we mentioned the importance of its positioning and the effects of shifting it forwards or backwards. In a mass customization environment, the position of CODP presents an utmost importance, because the balance between the flexibility and efficiency plays a critical role in mass customization environment compared to the manufacturing systems that only compete with efficiency or flexibility. There is interdependency among these two terms, CODP and mass customization. For locating the CODP, in other words while positioning the customer involvement, existing capabilities of the system and the customer requirements are used as inputs from mass customization environment. By considering these inputs for positioning CODP, the flexibility – efficiency balance is optimized. Therefore, CODP uses the inputs from mass customization environment, and affects it by balancing productivity – flexibility forces.

To be able to re-sequence and standardize the processes and the sub-processes for postponement, process modularity is essential (Feitzinger & Lee 1997). When some processes are moved downstream, closer to the end-user, it is expected that the processes should be performed as efficiently as before with at least with the same quality. Therefore, processes should have minimum or no dependency to each other in order to be re-sequenced for postponement, which indicates process modularity.

We state that product modularity provides rapid assembly and cost-efficiency for postponement. Although product modularity is not essential for postponement in every industrial sector (for example Mars, a Masterfoods company, delays the packaging and labeling of products until receiving customer orders in the Christmas season, and wine companies bottle wines in the local plants when they receive a customer order; and these products are not modular – Van Hoek 2001), modularity in product design increases the manufacturing speed or assembly speed (consequently, decrease lead time) where product architecture modularity is applicable such as electronics, automotive and machinery industries. It also provides cost-efficiency by decreasing the level of inventory by storing not high variety of finish products, but storing generic products and modules to customize it.

In the “relationship of postponement and CODP” section, we have illustrated how postponement moves the CODP downstream, closer to the end user. By postponing customization, lean part of the supply chain increases, which means efficiency (productivity) is emphasized. On the other hand, because customization is moved downstream, lead time is decreased, which means an increase in responsiveness (agility). Therefore, we can say that postponement is used to increase both leanness and agility which is essential for mass customization.

4.3 Model Illustration

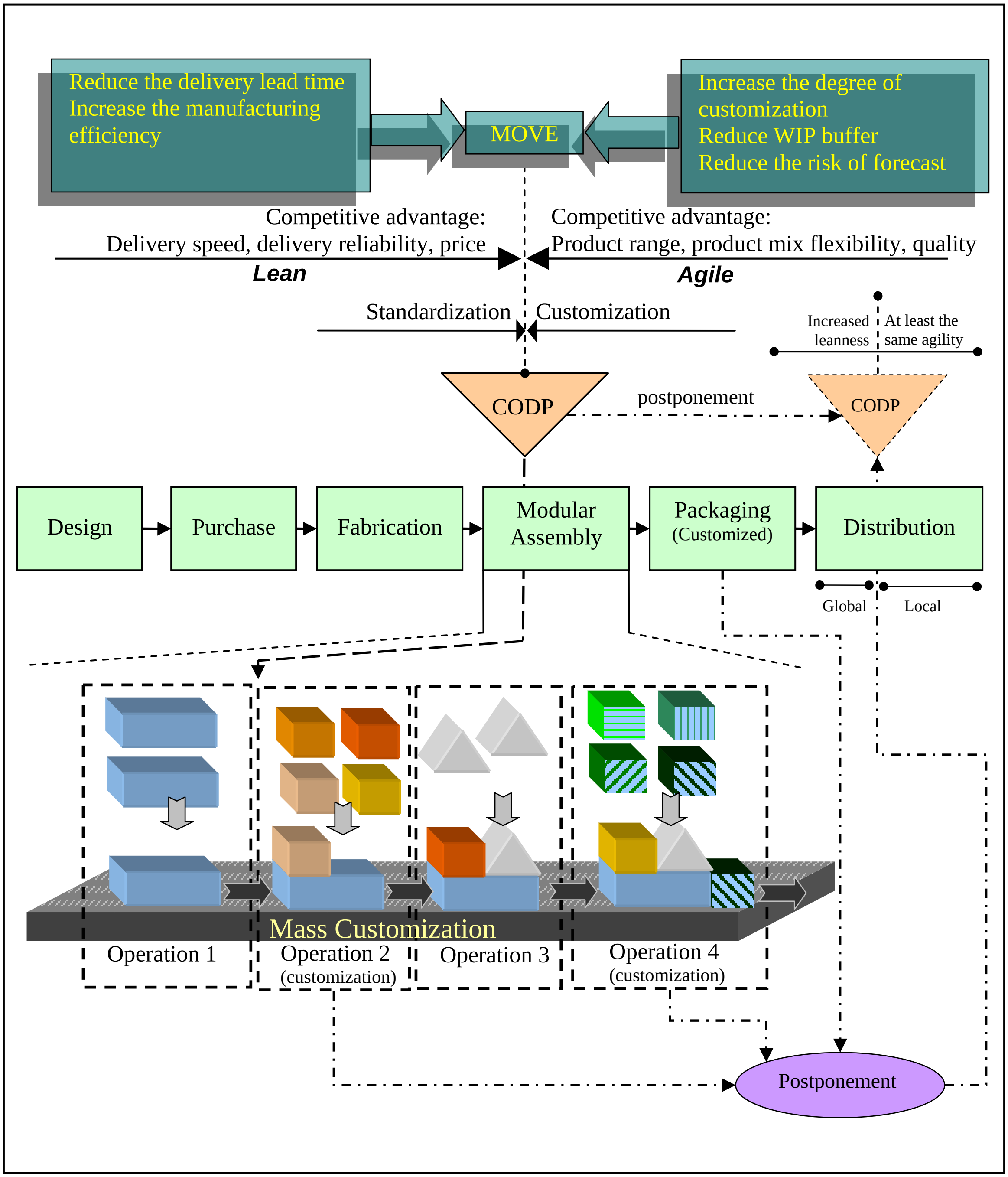

Figure 4-2: Model illustration of four concepts

In this part of the study, we will try to explain the dynamics of our four-concept-model on a model-illustration figure. We have identified the material flow of a mass customized modular product which is assembled to order. While building this figure, we have been inspired by the HP DeskJet case of Feitzinger and Lee (1997). So, in order to have better understanding of the figure, readers can think about HP case for clearer understanding.

We have discussed how the CODP separates the lean part and the agile part of the supply chain. We also mentioned that it is a strategic decision to position and to shift the position of CODP (Olhager 2003); it affects the competitive priorities, standardization-customization relationship and efficiency-flexibility balance. We also know that postponing a task (delayed differentiation) moves CODP upstream. In Figure 4-2 it is illustrated how postponement affects the CODP. Assembly operation 2, operation 4 and packaging process, which include customization, are postponed to be done at local warehouses. One important point to clarify here: postponing a customization supports the competitive advantages of moving the CODP downstream (delivery speed, delivery reliability, price), but this does not mean that it negatively affects the competitive advantages of moving the CODP upstream (product range, product mix flexibility, quality). After postponement, product range, product mix flexibility and quality are supposed to be at least at the same level, due to the product and process modularity. As well, postponement does not negatively affect the agility, although it reduces the agile part of the supply chain. Contrary, postponement decreases the lead time and increase delivery speed, which means a more responsive system.

In the model-illustration figure (Figure 4-2), we have emphasized that modular products are assembled on a mass customization platform, which means customization with a mass production efficiency. Assembly operation 1 and 3 do not include any customization, so the parts assembled there are always the same, but assembly operation 2 and 4 includes customization according to customer order, so the parts assembled there are illustrated with different colors and textures. By postponing the operation 2 and 4, only operation 1 and 3 is performed on the central manufacturing plant, and a generic semi-product inventory is held. This generic inventory is distributed to local warehouses, where customization occurs. By re-sequencing the processes, company groups the customization tasks downstream at local warehouses. In the beginning, customization was being performed at central manufacturing unit; but later, the customization part of the system is moved to local warehouses: it is performed with more efficiency. Therefore, we can call the whole system (supply chain) as mass customization.

5. Model Exploration in Autoliv Inc.

In this chapter, we will try to observe our model in a real company. We have chosen to visit a worldwide leading automotive safety company, Autoliv Inc. It is not sure that we can observe all the relationships in a single company, but we will try to find as much as we can. Our research method of exploration is interview and meeting. Due to the time constraint, we will leave more detailed analysis for future research.

In this chapter, we will first introduce the company. Then, we will research the material flow and four concepts in the firm. Finally, we will apply the model on Autoliv Inc. and try to point out the relationships we observed.

5.1 Firm Introduction

Throughout this section, company web site is used as source. All the information in section 5.1 is gathered from Autoliv’s web site.

Autoliv Inc. was established in 1997 as a merger of Europe's leading automotive safety company and the leading airbag manufacturer in North America and Asia. Prior to merger, both of these companies were guiding the industry by their innovative research and development. One pioneered in seatbelt technology and began manufacturing textile cushions for driver airbags using its new one-piece-weaving technology, and the other launched the first airbag system in 1980.

In 1998, Autoliv acquired half of the interests of Nokia’s and Sagem’s automotive related businesses in the field of electronics. In the same year, most of the assets of Sensor Technologies, a Japanese airbag and airbag sensor manufacturer, were bought; and Autoliv started to build a production plant in Japan. By the way, steering wheel production started in USA. In the following years, Autoliv Inc. continued to acquire companies of its industrial sector in Japan, Estonia, and China; arranged joint-ventures in Korea; and opened plant in Romania.

Now, Autoliv Inc. develops markets and manufactures airbags, seatbelts, safety electronics, steering wheels, anti-whiplash systems, seat components and child seats as well as night vision systems and other active safety systems. It employees 41800 people;

10 percent of them are in RD&E. It has 80 manufacturing facilities in 28 vehicle-producing countries and 20 crash test tracks in 12 countries.

Almost all major vehicle manufacturers and most vehicle brands are the customers of Autoliv Inc. Autoliv is not only a supplier for the vehicle manufacturers, it is also a development partner, which means that it recommends new safety-enhancing products, helps to adapt the products and conduct testing of the safety systems.

When we look at the sales of Autoliv Inc., more than half of the sales realizes in Europe (52%). North America (26%) and Japan (9%) follows Europe, the rest of the World counts for 11 percent. Major markets are United States (20%), Germany (15%), France (13%), Japan (9%), Great Britain (6%), Spain (5%) and Sweden (6%). With these statistics, Autoliv has a really strong position in the global market. For instance, it has approximately half of the global market share for side airbags, which are invented by Autoliv.

Manufacturing in Autoliv

Autoliv Inc. follows a manufacturing strategy which focuses on concentrating component production in a relatively few locations. However, assembly plants of these components are spread out for being close to customer sites. Autoliv follows just-in-time delivery strategy; sometimes it delivers several times in a day. It started to build sequence centers in some vehicle manufacturers' plants. In company's web site, it is stated that "these centers make final assembly and feed Autoliv's products into the car assembly line in the right order, i.e. in accordance with the car buyers' selections of colors and optional equipment. Almost every minute, the Autoliv sequence center receives a new order and already within two to five hours (depending on the product) the order is executed and the product delivered". This statement tells us much about Autoliv's postponement, customization and modularization strategy, which we will discuss later.

One of the Autoliv's manufacturing strategy is to have manufacturing capacity where major vehicle manufacturers are located or going to be located. So, Autoliv has more manufacturing facilities compared to other occupant restraint suppliers. Because its largest customers are located in high-wage countries, Autoliv's manufacturing is highly automated to be cost-efficient. The production lines, manufacturing machinery and equipments used in automation is developed and manufactured in-house by Autoliv

Automation to assure standardization and high-quality. Recently, Autoliv has begun to move its labor-intense production to low-wage countries due to the cost concern. Now, 47 percent of its labor force is located in such countries.

In their web site, they summarize their strategy as being vehicle manufacturers' first-choice supplier through:

- Technological leadership
- Complete system capabilities
- Highest-value safety system solutions
- Cost efficiency
- Quality excellence
- Global presence
- Highest level of service and engagement
- Dedicated and motivated employees

5.2 Four Concepts in Autoliv Electronics

We have visited Autoliv Electronics, Motala, to see how these four concepts are related each other in practice. In the facility of Autoliv Electronics in Motala, roll-over sensors, airbag control units and remote sensors of it, night vision systems and telematic systems are produced. This facility is one of the four main production centers of Autoliv Electronics; the other three is in France, Canada and China.

The relationship of the firm and its customers are very strong. New products are developed with cooperation. Because every customer has some specific needs, the products that are developed in cooperation result with customer-specific products. This means Autoliv does not serve automotive market fixed solutions which vehicle producers choose. Instead, Autoliv serves products which are developed in cooperation for a particular customer.

In every product platform, there are product families for a particular customer (vehicle producer) and in every product family there are different variants of products. For example, airbag control units of every different vehicle producer forms a different family of products. In this family, there are different products for different vehicle models of the same customer. And also, these products in a particular family requires customization according to the left-side steering wheel or right-side steering wheel and including roll-over function or not. The customization implies adjustments in both software and hardware of the product. Some vehicle manufacturers demand special colors of connectors according to their internal coloring policy of cables. Labeling is also a part of customization. Every customer has their own barcode system to trace the components, so products are labeled according to the customer order.

Product architecture of the airbag control units is partly modular. Remote sensors necessarily require to be placed several locations (2 fronts, 2 sides) on the car. So, these parts have to be modular. However, central control unit is designed for maximum performance for every specific customer. Therefore, integral design principles are applied rather than modularity.

Every airbag control unit has approximately 500 components and every remote sensor has nearly 10 components. Most of these components are supplied from one particular supplier, which takes a few weeks. As a design principle, Autoliv tries to use same components for different products as much as possible to increase the component commonality. Product life cycles are long due to the long-life cycle of cars and need for spare parts of cars even if that model of cars is not produced anymore. Approximately, airbag control units have a life cycle of 5 to 8 years.

Autoliv Electronics receives orders in daily bases. According to the distance of the final location, they meet the demand in one day up to one week. Sometimes they receive orders to be met in the same day. In order to meet demands on time, they keep the final product inventory of a few days for the high-volume products. Because the material lead time is relatively long, they also keep component inventory in relatively higher quantity compared to final product inventory.

For the customization of products, work-in-process inventory is used as a buffer. And also, some buffer inventory is held in manufacturing area. When an order of different product variety is received, manufacturing operations is set-up. This changeover process is quick and easy. For some of the operations such as software installation, product is recognized automatically with the help of barcode system. This operation does not require any set-up for producing different product variants.

Autoliv Electronics emphasizes lean principles in production. Capacity is tried to be used fully for efficiency. Production type can be named as batch production. Quantity of a particular variant is important in order to involve it in production.

5.3 Discussion about the Model in Autoliv Electronics

As we previously stated, lean principles are dominant in the manufacturing of the Autoliv Electronics products. It means that productivity force is greater than the flexibility force and it pushes the CODP downstream. The reason for why lean principles are applied hides beneath customer requirements and existing capabilities of Autoliv Electronics according to our model. Because customers have line production, in which efficiency is critical, they want their suppliers to be able meet their demand in a short period. Therefore, Autoliv Electronics positions the CODP downstream to reduce the lead time.

The exact position of the CODP is not clear. Normally, company keeps finished goods inventory and demands are met from here. So, the location of the CODP is placed at the end of the manufacturing. But, company also keeps some buffer inventory in the manufacturing area, which is used to meet the variability in the demand such as left-side steering wheel or right-side steering wheel customization. So, the CODP can be moved upstream for the customization of the products. For the low-volume products such as spare part production of old model cars, manufacturing is preceded according to the order; there is no finished goods inventory for these products. So, the CODP for the low volume products is at the beginning of the manufacturing.

Products of Autoliv Electronics are not designed for modularity. There can be many reasons for this such as improving the performance of the products, protecting the innovation from imitation or weight and space (volume) constraints. I think the main reason for using integral designs is that customers are powerful and they dominate the product development process. Products developed in cooperation can not be used for other customers. For example, if some functions of airbag control unit were assigned to some modules, it would be hard to convince the other customers for using the same modules because of the size or connector constraints, but it is still possible.

State-of-the-art for remote sensors requires modularity, because it should be placed different locations on the car. If we think the airbag control unit and the remote sensors of it as a product, we can call the remote sensors as modules where triggering function is assorted. These modules can be used in different product variants and also in different product families. Therefore, we can say that remote sensors contribute to economies of scale by providing module commonality.

The production system of Autoliv Electronics focuses on cost efficiency; and also it serves some customization. This customization is provided by product flexibility (the ability to introduce and modify products economically) and mix flexibility (the ability to change the range of the products made within a period). But, volume flexibility of the production system (the ability to operate economically at different product volumes) is not as developed as the production systems of mass customization. The system is as efficient as batch production not mass production. Some minimum amounts of orders are required to be produced. Therefore, it is hard to call the system as mass customization, but we can say that it is the early development phase of mass customization due to the efficiency and flexibility provided.

For the relationship of customization and modularity in Autoliv is not very strong. Kumar (2004) states that the companies in early stages of mass customization that seek to mass customize in other ways, may have no immediate need for modular product. And also, as we exemplified in beginning of section 3.1, for companies that achieve very low set-up cost and time, the benefits of modularity become insignificant. Therefore, the relationships that define the modularity as enabler and success factor of mass customization in our model can not be observed in Autoliv Electronics.

For the postponement strategy, we can analyze the sequence centers of Autoliv Inc. Manufacturing of airbag system parts are located in several places. For example, electronic parts such as remote sensors and airbag control unit are produced in Autoliv Electronics in Motala; steering wheels containing driver airbag are produced in USA. In sequence centers, parts coming from several locations are met. These centers, which are located inside the customer site or in a nearby area, perform customization and final assembly according to the customer order in a few hours. They feed the car assembly line with the customized products in the right order.

The key to the success of sequence centers is delaying differentiation as downstream as possible in the supply network. All the customization is done in a very near location, so there is almost no time consumption for the delivery of products. According to our model, Autoliv Inc. shifts the CODP downstream by postponing differentiation and increase the effectiveness and efficiency in the supply chain. One other thing that our model tells us is that Autoliv Inc. realizes this postponement strategy with the help of modularity of the customization processes. If the customization and final assembly processes were not modular, it would be impossible to move these operations to a nearby area.

6. Conclusion

In this paper, we have discussed how postponement, mass customization, modularization and the customer order decoupling point are related to each other. After an introduction to the thesis, we have explained every concept individually. We have mentioned the basic issues about the concepts in this chapter. We have tried to keep it short and simple in order to be more understandable. After explaining concepts individually, we have made a deeper research for finding out the relationships of concepts. By using the knowledge we gained from Chapter 3, we have built our model. Then, we have explored the model in Autoliv Electronics. Now, in this conclusion chapter, we will mention our finding about the concepts, our model, what we have gained from this model, implications for researchers and managers, and future research options.

Stable mass market of 60’s and 70’s are not valid for almost two decades now. Product life cycles have become shorter, and customers are now able to reach any products on earth by the help of internet. It is now easier for customers to find the exact product that they want. Because customers now have a strong weapon like internet, they get the right for demanding more. They want products which are customized according to their orders to be delivered the exact place they want and with a good price. For the manufacturers, unfortunately, this tendency of customers is not declining; it is accelerating.

Mass customization strategy has been invented as a response to the developments in marketing environment. Companies which insist on mass production in spite of developing customization demands can not catch the nature of the turbulent market. On the other side, companies which do not pay attention the cost efficiency and only focus on service and flexibility can not survive in the market. However, mass customization companies do not consider the unstable nature of the market as a threat or trouble. Contrary, this unpredictable nature of the marketplace is an opportunity for the mass customizers.

HP DeskJet case shows us that the success of mass customization hides under postponing the differentiation as late as possible in the supply chain. According to our model, the relationship of mass customization and postponement can be explained by the concept of leagility. Postponed manufacturing, assembly or labeling allows companies to separate standard (or generic) components from differentiated products. Delaying differentiation of the product contributes to the leanness and responsiveness which are required in the mass customization. Therefore, we can state that postponement creates more leagile supply chains in behalf of mass customization.

It is not an easy task to achieve mass customization and postponement strategies. At this point, modularization strategy works for achieving or helping the success of these strategies. According to our model, product architecture modularity contributes both postponement and mass customization by rapid assembly and cost efficiency. It is also an enabler and a success factor of mass customization in some cases where set-up cost is significant. For the postponement strategy, it is not possible to separate and delay any operation without achieving process modularity. Therefore, modularization is an important issue to consider for managers or researches who want to implement or investigate postponement and mass customization.

We have also researched the CODP, which we think that it is related to the other concepts. We have found that customer requirements and existing capabilities of the firm is an important issue to consider the position of the CODP. In addition, shifting the CODP upstream or downstream affects the flexibility-productivity balance. We stated the effects of shifting the CODP in part "2.4.2 Positioning the CODP", which should be considered by managers before making any adjustments in the supply chain. Other relationship that we stated about the CODP is the effect of postponement on the CODP. According to the literature we researched, our model indicates that postponing the differentiation shifts the CODP downstream. Therefore, for the managers who try to focus on delivery speed and reliability, postponement strategy can be recommended if flexibility-productivity balance is paid enough attention.

We have explored our model in Autoliv Electronics. We could not observe all the relationships that we have stated according to the literature because of the distinctive context of Autoliv Electronics. Products of Autoliv Electronics are not as modular as HP DeskJet and they have long product-life cycles compared to HP products. The production is based on batch system. They do not serve fixed options that customers choose; they develop products and solutions in cooperation with customers. We, however, observed many similarities with our model and the case of Autoliv Electronics. We stated that the company is in early development phase of mass customization and sequence centers of Autoliv Inc. realize postponement strategy. Although company does not utilize a modularization strategy, component commonality provides some benefits of modularization such as economies of scale. For the CODP, company positions it downstream to emphasize the lean principles, but the exact position of it can be changed due to the volume of the product and the customization required.

For the future search, it would be very useful to observe our model in a mass customization company that fully utilizes modularization. A company that provides options to customers by assembling different modules can be very interesting to explore our model. And also, a survey can be conducted for the relationships of concepts. Several companies from different industrial sectors which utilize postponement, modularization or mass customization strategies or strategically locate the CODP for the appropriate flexibility-productivity balance can be chosen as a sample. According to this survey, statistical analyses can be executed for investigating the industrial sectors in which our model is valid, statistically stronger relationships and weaker relationships, percentage of different modularization types utilized, percentage of the different postponement strategies utilized, mass customization levels according to the industries or statistical difference of the location of the CODP according to the industries. Moreover, subjective comments and personal recommendations of managers can be questioned in the survey to detect any missing relationship of the concepts.

Bibliography

Alderson, W. (1950). "Marketing efficiency and the principle of postponement", *Cost and Profit Outlook*, Vol 3, pp 15–18.

Allen, K.R. and Carlson-Skalak, S. (1998). *Defining Product Architecture During Conceptual Design*, Proceedings of the 1998 ASME Design Engineering Technical Conference, Atlanta, GA.

Autoliv Inc. (2006), *Autoliv Inc. Official Web Site* retrieved January, 2008 – http://www.autoliv.com

Aviv, Y. and Federgruen, A. (1998). *The benefits of design for postponement. Quantitative Models for Supply Chain Management, edited by S. Tayur, R. Ganeshan and M. Magazine*, Kluwer Academic Publishers, Dordrecht.

Baldwin, C.Y. and Clark, K.B. (1997). "Managing in an Age of Modularity", *Harvard Business Review*, Vol 75, No 5, pp 84 – 93.

Berry, W.L. and Hill, T. (1992). "Linking systems to strategy", *International Journal of Operations and Production Management*, Vol 12, No 1, pp 3 – 15.

Bhattacharya, A.K., Jina, J. and Walton, A.D. (1996). "Product Market Turbulence and Time Compression", *International Journal of Operations and Production Management*, Vol 16, pp 34 – 47.

Bowersox, D.J. (1978). *Logistical Management*, Macmillan, New York.

Bowersox, D.J. (1995). *World class logistics, the challenge of managing continuous change*. Council of Logistics Management, Oak Brook, II.

Bowersox, D.J., Carter, P.L. and Monczka, R.M. (1993). "Materials logistics management", *International Journal of Physical Distribution & Logistics Management*, Vol 23, No 5, pp 46 – 51.

Bowersox, D.J. and Closs, D.J. (1996). *Logistical management: The Integrated Supply Chain Process*, McGraw-Hill, New York.

Brown, A., Lee, H. and Petrakian, R. (2000). "Xilinx Improves Its Semiconductor Supply Chain Using Product and Process Postponement", *Interfaces*, Vol 30, pp 65 – 80.

Bucklin, L. P. (1965). "Postponement, speculation and the structure of distribution channels", *Journal of Marketing Research*, Vol 2, pp 26 – 31.

Chen, W. (1987). *A theory of modules based on second-order logic*, Proceedings of the IEEE Logic Programming Symposium, pp 24 – 33.

Christopher, M. (2000). "The Agile Supply Chain: Competing in Volatile Markets", *Industrial Marketing Management*, Vol 29, No 1, pp 37 – 44.

Comstock, M. 2004. *Production Systems for Mass Customization: Bridging Theory and Practice*, Linköping Studies in Science and Technology Dissertation No.894, Linköping, Sweden.

Comstock, M. and Winroth, M. (2001). *Enabling Mass Customization in the Mobile Telephone Industry: Agility, Flexibility and the Changing Role of Assembly at Ericsson*, Proceedings of the 34th CIRP International Seminar on Manufacturing Systems, pp 195 – 204, 16 – 18 May, Athens, Greece.

Da Silveira, G., Borenstein, D. and Fogliatto F.S. (2001). "Mass customization: Literature review and research directions", *International Journal of Production Economics*, Vol 72, pp 1 – 13.

Davila, T. and Wouters, M. (2007). "An Empirical Test of Inventory, Service and Cost Benefits from a Postponement Strategy", *International Journal of Production Research*, Vol 45, No 10, pp 2245 – 2267.

Davis, S. (1987). *Future Perfect*, Addison-Wesley Publishing, Reading, MA.

Duray, R. (2002). "Mass Customization Origins: Mass or Custom Manufacturing?", *International Journal of Operations and Productions Management*, Vol 22, No 3, pp 314 – 328.

Duray, R., Ward, P.T., Milligan, G.W. and Berry W.L. (2000). "Approaches to Mass Customization: Configurations and Empirical Validation". *Journal of Operations Managements*, Vol 18, pp 605 – 625.

Feitzinger, E. and Lee, H.L. (1997). "Mass customization at Hewlett-Packard: the Power of Postponement", *Harvard Business Review*, Vol 75, 116 – 121.

Fine, C.H. (1998). *Clockspeed – Winning Industry Control in the Age of Temporary Advantage*, Perseus Books, Reading, MA.

Gershenson J.K., Prasad, G.J. and Zhang, Y. (2004). "Product modularity: measures and design methods", *Journal of Engineering Design*, Vol 15, No 1, pp 33 – 51.

Gershenson, J.K., Prasad, G.J. and Allamneni, S. (1999). "Modular Product Design: A Life-Cycle View", *Journal of Integrated Design and Process Science*, Vol 3, pp 3 – 26.

Gershenson, J.K., Prasad, G.J. and Zhang, Y. (2003). "Product modularity: definitions and benefits", *Journal of Engineering Design*, Vol 14, No 3, pp 295 – 313.

Gilmore, J. and Pine, J. (1997). "The four faces of mass customization", *Harvard Business Review*, Vol 75, pp 91 – 101.

Hart, C. (1995). "Mass customization: Conceptual underpinnings, opportunities and limits", *International Journal of Service Industry Management*, Vol 6, No 2, pp 36 – 45.

Hart, C. (1996). "Made to order", *Marketing Management*, Vol 5, No 2, pp 10 – 23.

Heilala J. and Voho P. (2000). *Modular reconfigurable flexible final assembly systems in electronic industry*, TU Delft Assembly Automation Workshop, 11-12 May

Hill, T. (2000). *Manufacturing Strategy—Text and Cases, 2nd Edition*. Palgrave, Houndmills, Hampshire.

Hoekstra, S. and Romme, J. (1992). *Integrated Logistics Structures: Developing Customer Oriented Goods Flow*, McGraw-Hill, London.

Huang, C.C. and Kusiak, A. (1998). “Modularity in Design of Products and Systems”, *IEEE Transactions on Systems: Man and Cybernetics Part A*, Vol 28, No 1, pp 66 – 77.

Kotha, S. (1995). “Mass Customization: Implementing the Emerging Paradigm for Competitive Advantage”, *Strategic Management Journal*, Vol 16, pp 21 – 42.

Kotha, S. (1996). “From mass production to mass customization: The case of the National Industry Bicycle Company of Japan”, *European Management Journal*, Vol 14, No 5, pp 442 – 450.

Kotha, S. (1996). “Mass-customization: a strategy for knowledge creation and organizational learning”. *International Journal of Technology Management*, Vol 11, No 7, pp 846 – 858.

Krajewski, L., Wei, J.C. and Tang, L.L. (2005). “Responding to Schedule Changes in Build-To-Order Supply Chains”. *Journal of Operations Management*, Vol 23, pp 452–469.

Kumar, A. (2004). “Mass Customization: Metrics and Modularity”. *The International Journal of Flexible Manufacturing Systems*, Vol 16, pp 287 – 311.

Lampel, J. and Mintzberg, H. (1996). ”Customizing customization”, *Sloan Management Review*, Vol 38, pp 21 – 30.

Lee, H.L. (1998). *Postponement for Mass Customization: Satisfying Customer Demands for Tailor-Made Products. Strategic Supply Chain Alignment* (Gattorna, J. Edition), Gower, Brookfield, VT, pp 77 – 91.

Marshall, R., Leaney, P.G. and Botterell, P. (1998). “Enhanced Product Realization through Modular Design: An Example of Product/Process Integration”, *Journal of Integrated Design and Process Technology*, Vol 3, pp 143–150.

Mason-Jones, R., Naylor, B. and Towill, D.R. (2000). “Engineering the Leagile Supply Chain”, *International Journal of Agile Management Systems*, Vol 2, No 1, pp 54 – 61.

Mikkola, J. (2007). “Management of Product Architecture Modularity for Mass Customization: Modeling and Theoretical Considerations”, *IEEE Transactions on Engineering Management*, Vol 54, No 1, pp 57 – 69.

Mikkola, J.H. and Gassmann, O. (2003). “Managing Modularity of Product Architectures: Toward and Integrated Theory”, *IEEE Transactions on Engineering Management*, Vol 50, No 2, pp 204 – 218.

Nair, A. (2005). “Linking Manufacturing Postponement, Centralized Distribution and Value Chain Flexibility with Performance”, *International Journal of Production Research*, Vol 43, pp 447–463.

Naylor, J.B., Naim, M.M. and Berry, D. (1997). "Leagility: integrating the lean and agile manufacturing paradigm in the total supply chain", *MASTS working paper No. 47 Re-published in International Journal of Production Economics (1999)*, Vol 62, pp 107 – 118.

Newcomb, P.J., Bras, B. and Rosen, D.W. (1996). *Implications of Modularity on Product Design for the Life Cycle*, Proceedings of the 1996 ASME Design Engineering Technical Conferences – 8th International Conference on Design Theory and Methodology, Irvine, CA.

Olhager, J. (2003). "Strategic Positioning of the Order Penetration Point", *International Journal of Production Economics*, Vol 85, pp 319 – 329.

Pillar, F. (2004). "Mass Customization: Reflections on the State of the Concept", *The International Journal of Flexible Manufacturing Systems*, Vol 16, pp 313–334.

Pimmler, T. U. and Eppinger, S. D. (1994). *Integration Analysis of Product Decompositions*, Proceedings of the 1994 ASME Design Engineering Technical Conferences—6thInternational Conference on Design Theory and Methodology, Minneapolis, MA.

Pine, J. (1993). "Mass customizing products and services", *Planning Review*, Vol 21, No 4, pp 6 – 13.

Pine, J., Victor, B. and Boyton, A. (1993). "Making mass customization work", *Harvard Business Review*, Vol 71, No 5, pp 108 – 111.

Rudberg, M. and Wikner, J. (2004). "Mass Customization in terms of the Customer Order Decoupling Point", *Production Planning & Control*, Vol 15, No 4, pp 445 – 458.

Schilling, M.A. (2000). "Toward a General Modular Systems Theory and its Application to Interfirm Product Modularity", *Academy Management Review*, Vol 25, No 2, pp 312 – 334.

Shapiro, R. D. (1984). "Get leverage from logistics", *Harvard Business Review*, Vol 62, pp 119 – 126.

Sharman, G. (1984). "The Rediscovery of Logistics", *Harvard Business Review*, Vol 62, pp 71 – 80.

Shingo, S. (1981). *Study of Toyota Production System from Industrial Engineering Viewpoint*, Japan Management Association, Tokyo.

Skinner, W. (1969). "Manufacturing—Missing Link in Corporate Strategy". *Harvard Business Review*, Vol May-June, pp 136 – 145.

Skipworth, H. and Harrison, A. (2004). "Implications of Form Postponement to Manufacturing: A Case Study", *International Journal of Production Research*, Vol 42, No 10, pp 2063 – 2081.

Sosale, S., Hashemian, M., and Gu, P. (1997). "Product Modularization for Reuse and Recycling". *Concurrent Product Design and Environmentally Conscious Manufacturing*, ASME, DE-94/MED 5, pp 195 – 206.

Spira, J. (1996). “Mass customization through training at Lutron Electronics”, *Computers in Industry*, Vol 30, No 3, pp 171 – 174.

Tu, Q., Vonderembse, M. A., Ragu-Nathan, T.S. and Bhanu Ragu-Nathan (2004). “Measuring Modularity-Based Manufacturing Practices and Their Impact on Mass Customization Capability: A Customer-Driven Perspective”. *Decision Sciences*, Vol 35, No 2, pp 147 – 168.

Ulrich, K. (1995). “The Role of Product Architecture in the Manufacturing Firm”, *Research Policy*, Vol 24, No 3, pp 419 – 440.

Ulrich, K. and Eppinger, S.D. (1995). *Product Design and Development*, McGraw-Hill, New York.

Ulrich, K. and Tung, K. (1991). *Fundamentals of Product Modularity*, Proceedings of the 1991 ASME Design Engineering Technical Conferences – Conference on Design/Manufacture Integration, Miami, FL.

Van Hoek, R.I. (2000). “The Thesis of Leagility Revisited”, *International Journal of Agile Management Systems*, Vol 2, pp 196 – 201.

Van Hoek, R.I. (2001). “The Rediscovery of Postponement: a Literature Review and Directions for Research”, *Journal of Operations Management*, Vol 19, 161–184.

Vollmann, T.E., Berry, W.L. and Whybark, D.C. (1997). *Manufacturing Planning and Control Systems, 4thEdition*, Irwin/ McGraw-Hill, New York.

Waller, M.A., Dabholker, P.A. and Gentry, J.J. (2000). “Postponement, Production Customization, and Market-Oriented Supply Chain Management”. *Journal of Business Logistics*, Vol 21, pp 133 – 160.

Wikner, J. and Rudberg, M. (2005). “Integrating Production and Engineering Perspectives on the Customer Order Decoupling Point”. *International Journal of Operations & Production Management*, Vol 25, No 7, pp 623 – 641.

Yang, B. and Burns, N. D. (2003). “The Implications of Postponement for the Supply Chain”. *International Journal of Production Research*, Vol 41, No 9, pp 2075 – 2090.

Yang, B., Burns, N.D. and Backhouse, C.J. (2004a). “Postponement: A Review and an Integrated Framework”, *International Journal of Operations & Production Management*, Vol 24, No 5, pp 468 – 487.

Yang, B., Burns, N. and Backhouse, C.J. (2004b). “Management of Uncertainty through Postponement”. *International Journal of Production Research*, Vol 42, No 6, pp 1049 – 1064.

Zhang, Y., Gershenson, J.K. and Allamneni, S. (2001). *An initial study of the retirement costs of modular products*, Proceedings of the 2001 ASME Design Engineering Technical Conferences – 13th International Conference on Design Theory and Methodology Pittsburgh, PA.

Zinn, W. and Bowersox, D.J. (1988). “Planning Physical Distribution with the Principle of Postponement”, *Journal of Business Logistics*, Vol 9, pp 117–136.

Zinn, W. and Levy, M. (1988). "Speculative inventory management: a total channel perspective", *International Journal of Physical Distribution and Materials Management*, Vol 18, No 5, pp 34 – 39.