Complexity and Variety in Mass Customization Systems: Analysis and Recommendations

Abstract

Purpose – To identify and examine the origins of complexity in a mass customization system and to propose an *effective* application sequence of variety management strategies in order to cope with this complexity.

Design/methodology/approach – Through the application of Suh's complexity theory an understanding of the causes of complexity in the specific context of a mass customization environment is developed. This facilitates the identification of the strategies that are adequate to tackle the problems induced by complexity.

Findings – The mass customization system is a coupled system that cannot be mastered simply. It is definitely impossible to transform it to an uncoupled system with low complexity level. However, the effective and targeted implementation of variety management strategies at the product and process levels enables the management of this complexity by making the system more decoupled.

Practical implications – Complexity can be decreased if managers ensure less dependency between the satisfaction of customer requirements and position of the decoupling point. It is also advantageous to reduce the coupling level between fast delivery requirement in mass customization and the decoupling point placement. Furthermore, an effective variety management calls for the implementation of the identified strategies in an ascending order of complexity reduction potential.

Originality/value – The article relates the complexity theory of Suh to mass customization system, provides a framework for the classification of variety management strategies and derives managerial recommendations so as to reduce the complexity in a mass customization environment.

Key words – Mass customization, Suh's complexity theory, Variety management strategies

Paper type Conceptual paper

Introduction

Mass customization is a business strategy that aims at satisfying individual customer needs at costs that do not considerably differ from the costs of similar standard products (Pine, 1993; Tseng and Jiao, 1996). The term mass customization can be regarded as an oxymoron because it joins two business strategies that seem to be a priori incoherent, namely differentiation and cost leadership (e.g. Piller, 2006). The companies which embark on mass customization tend to provide their customers with a large product mix (called solution space); so as to increase the chance that everyone finds the product that exactly corresponds to his or her requirements (Pine, 1993). However, the design, development, production and distribution of a large product variety can adversely affect efficiency (e.g. Lingnau, 1994; Fisher and Ittner, 1999). The result can be a drastic increase of costs and considerable reduction of profit. The costs of variety emerge in the form of overheads (also called hidden costs) and are generally referred to as complexity costs in the business administration literature (e.g. Child et al, 1991). Because of this, the capability of managing variety and complexity seems to be a necessary competence for firms that plan to pursue mass customization (Blecker et al., 2005).

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While many authors argue that mass customization triggers high complexity, there is, however, a little evidence about the type or nature of complexity that is caused in such environments. In mass customization literature, the term complexity is mostly used without having been defined first. Furthermore, variety and complexity are oftentimes used interchangeably as if they were equivalent terms. However, in order to effectively manage complexity, we believe that it is necessary to argue about a common framework, which provides an unambiguous interpretation of the term. Such a framework will enable a better understanding of the causes and effects of complexity. Toward this aim, we choose the complexity theory that is set forth by Suh (2005). Subsequently, we explore the mass customization system form this perspective. In this way, we are able to have a better understanding of the origins of complexity in a mass customization environment. For the management of this complexity, we argue the potential of variety management strategies that have been developed thus far. More importantly, it is shown that these strategies have unequal potentials of complexity reduction. The paper concludes that in order for managers to reduce the complexity of a mass customization system, they have to ensure that over time, customer requirements and customization responsiveness are both independent from the position of the decoupling point, the point at which the customer order penetrates. Taking this into account, a logical sequence according to which variety management strategies should be implemented in practice, is proposed. Finally, the paper demonstrates that the mere application of modularity can be regarded as a necessary but not a sufficient condition in order to lead mass customization to success. In effect, some complexity problems will still arise, in spite of the implementation of modular structures.

Suh's Complexity Theory

Mathematicians, biologists, chemists, physicists, biologists, computer scientists and economists did not agree about a common interpretation of complexity. In effect, the problems dealt with in each field of research have shaped the meaning of the term. Complexity may be equated with system entropy (Shannon, 1948), logical depth (Bennett, 1988), algorithmic complexity (Chaitin, 1987), a state lying between order and randomness, schema representing the system regularities (Gell-Mann, 1994), number of parts and their interactions in a system (e.g. Luhmann, 1996), or even ignorance (Yates, 1978). In the field of business administration and operations management, in order to analyze the complexity of the firm, researchers may use the system theoretical point of view which is taken over from the field of cybernetics. This perspective considers the firm as a system in which different entities (e.g. departments or functions) interact with each other in order to transform a certain input to an output. On the other hand, the entropic measure has been successfully applied to examine the complexity of manufacturing systems (e.g. Deshmukh et al., 1998; Frizelle and Woodcock, 1995) or supply chains (e.g.; Sivadasan et al., 2002).

As stated previously, in our analysis we will use the complexity theory of Suh in order to address some of the complexity issues in mass customization. Suh's complexity theory is based on axiomatic design. Suh (1999, p. 117) points out that "[m]any of the past ideas of complexity are not consistent with that defined in axiomatic design. In many of the past works, complexity was treated in terms of an absolute measure. In axiomatic design, information and complexity are defined only relative to what we are trying to achieve and/or want to know." Whereas the axiomatic design was originally developed to provide designers with a scientific method for the evaluation and analysis of alternative product designs, the approach was successfully applied for the identification of good manufacturing system designs. Axiomatic design defines four domains of the design world, which are: the customer domain, functional domain, physical domain and process domain. For the definition of complexity, only the functional domain and physical domain need to be explained. The functional domain refers to what should be fulfilled, whereas the physical domain describes how the functional requirements are satisfied. The functional requirements (FRs) ascertain the design range whereas the design parameters (DPs) define the system range. In this context, Suh (2005) defines complexity as a measure of uncertainty in achieving the specified FRs, where each FR is considered as a continuous random variable with a specific probability density function. In this framework, there are two kinds of complexity. The first type is the time-independent complexity, which is, in turn, divided into real and imaginary complexities. The second type is time-dependent and may be divided into combinatorial and periodic complexities.

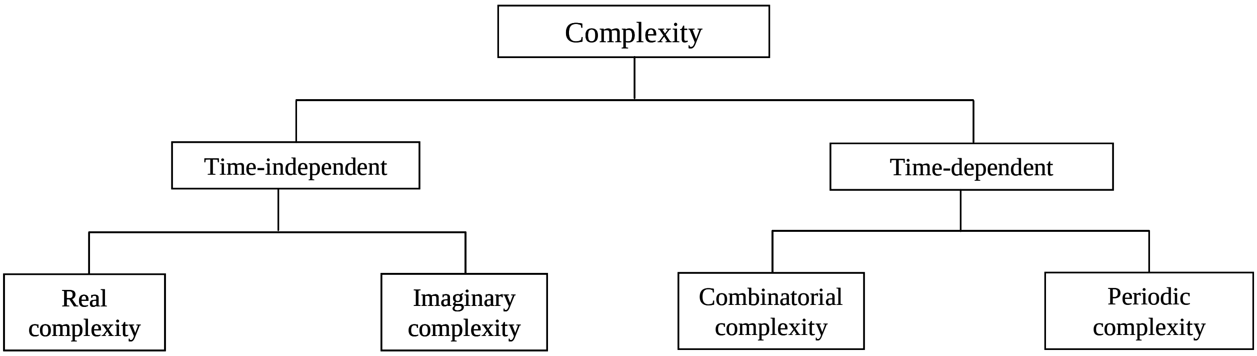

Figure 1: Complexity definition by Suh (2005)

Time-independent real complexity

Time-independent real complexity arises when the system range is not embodied in the design range. In other words, there is an uncertainty in achieving the FRs with the current system design. Thus uncertainty decreases if the common range which is the intersection area of the system and design ranges increases (figure 2). In fact, the un-shaded area of the system range defines this uncertainty or the probability that the current design fails in fulfilling the desired functional requirements.

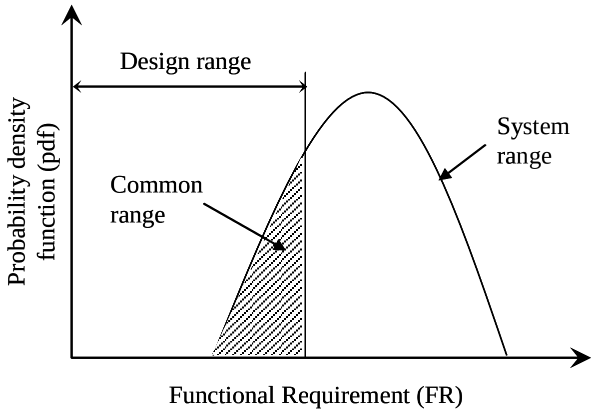

Figure 2: Design range, system range and common range in axiomatic design (Suh, 1990)

Time-independent imaginary complexity

Imaginary complexity is triggered by the lack of knowledge and understanding of the specific design. Suh (2005) illustrates imaginary complexity by means of the design matrix which ensures the mapping from the design range to the system range. The number of rows of this design matrix is equal to the number of FRs, whereas the number of columns is equal to the number of DPs. In order to avoid coupled designs (Number of DPs < Number of FRs) or redundant designs (Number of FRs < Number of DPs), the number of FRs must be usually equal to the number of DPs (number of FRs = number of DPs = n). Suh points out that if this matrix is diagonal, one can change any design parameter to adjust the corresponding functional requirement without affecting any other FR. This type of design is optimal and is referred to as uncoupled design. However, in the event that there are nonzero elements above and under the diagonal line of the matrix, the design is coupled. This type of design is not desirable because any change in a design parameter does not affect only one FR but a set of FRs. On the other hand, Suh demonstrates that for any design problem, a triangular design matrix exists, which maps the set of FRs to DPs. The corresponding design is called decoupled design. From this, it follows that the designer who wants to remove the real complexity from the system, has to consider the set of DPs in the order provided by the diagonal matrix. Otherwise, an imaginary complexity will be perceived since the designer has to try n! different combinations of DPs to satisfy the FRs.

Time-dependent combinatorial complexity

Combinatorial complexity is an "event-driven" complexity. It arises when the system range moves away from the design range in the course of time because of the unpredictability of several future events. Suh (2005) provides the scheduling function of a job shop manufacturing system as an example for combinatorial complexity. In effect, the future scheduling is affected by decisions made earlier in the past and the system may exhibit a combinatorial complexity over time, which leads to a chaotic state or system failure.

Time-dependent periodic complexity

"The periodic complexity is defined as the complexity that only exists in a finite time period, resulting in a finite and limited number of probable combinations" (Suh, 2005, p. 72). Thus it is desirable to prevent the system range from continuously moving away from the design range by transforming combinatorial complexity to periodic complexity.

Exploring Mass Customization from the Perspective of Suh's Complexity Theory

Most of previous work in the field of variety and complexity management argues that the proliferation of product variety is a main driver of operational complexity, which in turn raises costs (e.g. MacDuffie et al. 1996). This has even led many researchers to consider the number of products and internal parts as an indicator of complexity. Thus according to this perception, every system (of supply, production, distribution etc.) constrained to handle an extensive variety may be referred to as complex. While this can be true, the main unclarity concerns the complexity definition that is used in this regard. To the best of our knowledge, there is not a large body of research that analyzes the mass customization system under a scientific definition of complexity, except for e.g. the work of Blecker and Abdelkafi (2006) who develop an entropic measure based on the weighted Shannon entropy in order to evaluate the complexity of assemble-to-order systems. Therefore, in this section, we intend to fill this gap by using Suh's complexity theory, which has already been applied with success for the analysis and optimization of manufacturing systems.

The Mass Customization Production System

Mass customization generally calls for the postponement principle that is to delay some of the value adding activities until a customer order arrives. This principle actually appears to be a necessary requirement if the customer preferences have to be considered. The mass customization production system consists of two main subsystems. The first is a push subsystem which transforms raw materials and supplied components into subassemblies and/or semi-finished products. In this part of the system, production occurs according to forecasts. The second subsystem is a pull system, which is customer-driven and aims to build products that match customer requirements (figure 2). It is worth noting that in the following analysis, we only consider the production system of the firm which receives the orders from the final consumers. Consequently, a more comprehensive perspective including supply chain issues in mass customization will not be pursued.

The push and pull parts of the production system are separated by the customer order decoupling point. At this point, the company keeps inventories of subassemblies and semi-finished products. As the decoupling point moves upstream in the value chain, the degree of customization is expected to increase *ceteris paribus* because customers would have the possibility to affect the production process at earlier stages. The decoupling point may not only influence the customization level but also delivery time. If it is closer to the customer, shorter delivery times can be achieved. However, if it is placed at the beginning of the production process, it could be assumed that longer delivery times would be necessary.

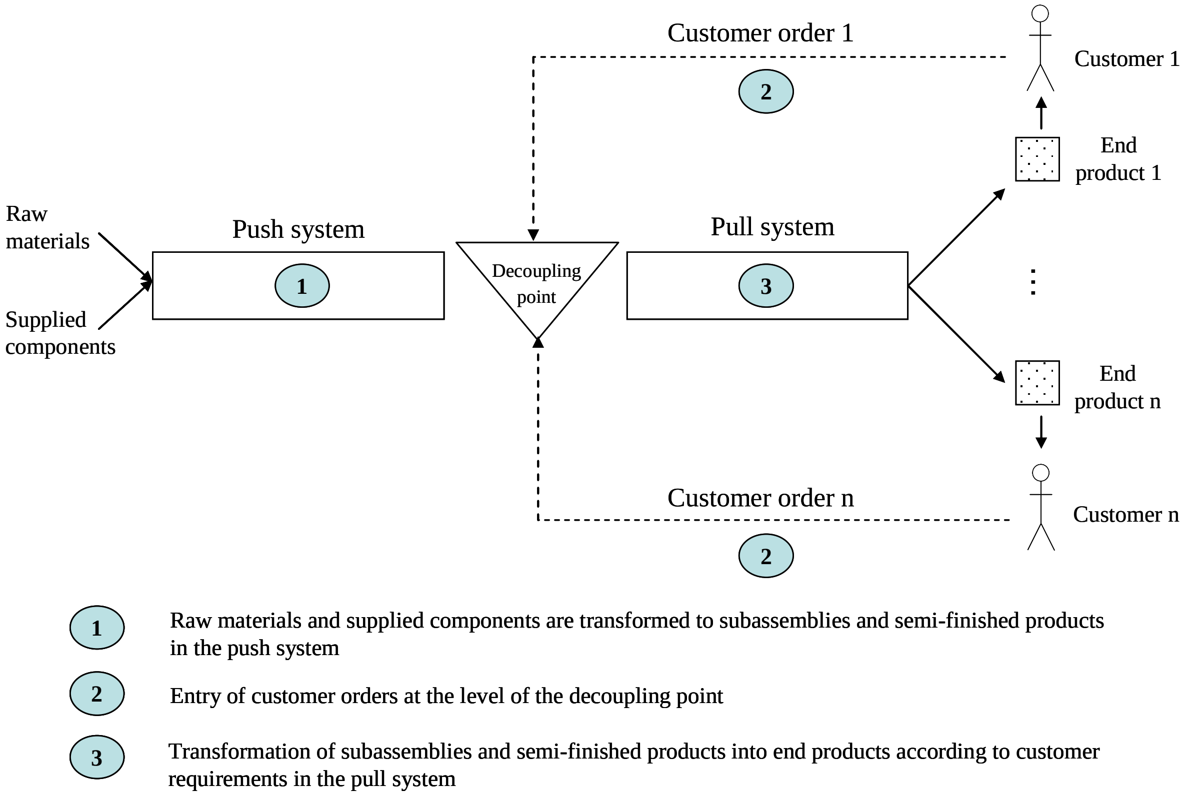

Figure 2: A simplified view of the mass customization production system

Complexity of the Mass Customization Production System

In order to adequately use Suh’s complexity theory, we shall determine at first the functional requirements that should be fulfilled by the production system in a mass customization environment. Recall that by definition, mass customization strives to satisfy individual customer requirements. The objective of the strategy cannot be achieved if the differences between customer preferences are not recognized and served differently. Therefore, the first functional requirement is FR_1 = Satisfy customer requirements. For instance, according to Piller (2006), customer requirements can be satisfied along three main dimensions which are: design, fit and functionalities. The second functional requirement is the capability of producing efficiently so that the prices of customized products stay at a comparable level to the prices of similar standard products. In this context, Rautenstrauch et al. (2002) and Blecker et al. (2005) speak of a moderate surcharge that should not exceed 10-15% the price of standard products. Subsequently, FR_2 = Produce economically. The third functional requirement that we identify is FR_3 = Deliver fast. In effect, after order placement, customers have to wait a certain time until the customized good is produced and shipped to them. Although customers are willing to wait, they do not accept any delivery time. For instance, Holweg and Miemczyk (2002) report on some examples from the automotive industry that illustrate the attempts of car manufacturers to reduce order-to-delivery lead time with the objective to enable build-to-order and mass customization. For instance, Renault, Ford and VW have had similar goal to produce vehicles in 14 or 15 days, whereas BMW aimed a ten-day order-to-delivery lead time. While not all of these projects achieved the targeted results (e.g. the Projet Nouvelle Distribution by Renault could not reach its objectives, thereby obliging Renault to redefine the original targets from 14 days to 20 days order-to-delivery), the examples clearly demonstrate the importance of fast delivery in mass customization or at least the delivery within the timeframes that are acceptable by customers. It should be noted that since we do not consider the entire supply chain perspective, we mean by fast delivery the capability of the manufacturing system of producing customized goods in a fast-paced manner. Our choice of these particular functional requirements is also well founded in existing literature. For instance, Tu et al. (2001) developed a measure for the evaluation of mass customization capabilities that is based on three main components: (1) customization cost-effectiveness: the ability to differentiate products without increasing manufacturing costs significantly, (2) customization volume effectiveness: the ability to increase variety without decreasing production volume, and (3) customization responsiveness: the ability to reduce order-to-delivery time of customized products and to reorganize processes quickly according to customization requests. Whereas the first and second capabilities can be subsumed under the second functional requirement (FR_2 = Produce economically), the third capability refers to the third functional requirement (FR_3 = Fast delivery). On the other hand, the satisfaction of specific customer requirements is an implicit component for the evaluation of mass customization capabilities in Tu et al.’s model.

In order to satisfy the functional requirements and make the system work, certain design parameters should be ascertained. We identify three critical design parameters, which are: DP_1 = Product variety, DP_2 = Position of the decoupling point and DP_3= Production flow. In fact, the determination of the design parameters has relied on experience and practical involvement in previous mass customization projects. Suh (1990) also argues that designers may have different views with regard to the choice of the design parameters required to solve a specific design problem. Product variety is required for the fulfillment of a wide range of customer requirements. The placement of the decoupling point represents a critical decision that affects the level of customization and waiting time until delivery. Finally, the flow of production is closely related to the organization of the production process. For instance, job shop manufacturing in the pull system will trigger long lead times and large inventories. On the other hand, a paced assembly line would trigger fewer work-in-process inventories, while ensuring short lead times. For sure, this comes at the cost of flexibility since paced assembly lines generally involve fewer product varieties than job shop manufacturing systems. The work by Ramdas (2003) to a large extent supports the choice we have made with respect to the design parameters. The author mentions that variety-related decisions in general can be viewed as focusing on variety creation and variety implementation. Variety creation decisions include four key decision issues: 1) dimensions of variety, 2) product architecture, 3) degree of customization, and 4) timing. Variety implementation decisions are related to three main issues, namely: 1) process capabilities, (2) points of variegation or “decoupling”, and 3) day-to-day decisions. In fact, the dimensions of variety, product architecture and degree of customization can be subsumed under the design parameter that we call: product variety. Process capabilities refer to the design parameter: production flow, whereas the point of variegation obviously corresponds to the design parameter which relates to the position of the decoupling point. Timing and day-to-day decisions both refer to the time component that we do not consider at this stage, but the role of this component will be clear after we study the design matrix in more details and especially the effects of combinatorial complexity.

It is worth noting that the design task of a mass customization system should involve many experts from different areas within the company, especially managers form marketing, product development, purchasing, production and internal logistics. The success of a mass customization strategy starts with an adequate understanding of customers' preferences. The marketing managers should ascertain if customers need customized products or not. Subsequently, they should determine the range of product attributes and functionalities to be offered to the market. Thus, the specification of FR_1 (Satisfaction of customer requirements) is to large extent a marketing decision. Product development should ensure that customer requirements are translated into concrete product variety. The managers in this area have a major influence on DP_1 (product variety) and also on DP_2 (position of the decoupling point) because the product architecture largely influences the position of the decoupling point. After that, purchasing and production managers have to collaborate in order to make optimal make or buy decisions. Production managers have a major role in the mass customization system design. They should ensure the achievement of functional requirement FR_2 (efficient production) and FR_3 (Deliver fast) through a close collaboration with the managers from internal logistics through an adequate choice of DP_3 (production flow) and DP_2 (placement of the decoupling point).

To determine the design matrix of the mass customization system, a thorough examination of the relationships between the functional requirements and design parameters is necessary (figure 3). This design matrix is a square matrix owing to equal number of FRs and DPs. The first functional requirement (FR_1) representing the satisfaction of customer requirements only relates to product variety (DP_1) and decoupling point's position (DP_2). Indeed, it is straightforward that in order for companies to increase the *chance* that a wide range of customer requirements is satisfied, a larger product variety (solution space) is required. It is worth noting that product variety does not guarantee that customers find exactly what they want. It only ensures that it is more likely that customer preferences can be matched with products actually existing in the assortment. On the other hand, as explained previously, the location of the decoupling point can influence the customization level. In effect, the decoupling point is not only the boundary between the push and pull systems but also the point at which the customer order enters the value chain. However, the degree of fulfillment of customer needs and production flow (DP_3) are uncorrelated and subsequently $A_{13} = 0$. In this context, we notice again that customer requirements should not be confused with product variety. In fact, it is product variety that can disturb the production flow but not customer requirements. The second functional requirement reflects the system efficiency, which can be affected by all three design parameters, namely product variety, position of the decoupling point and production flow. For instance, an empirical study of Wildemann (1995) has shown that with the doubling of product variety, unit costs increase about 20-35% for firms with traditional manufacturing systems. For segmented and flexible plants, unit costs would increase about 10-15%. This result shows that efficiency not only depends on product variety but also on the production flow inside the system. In addition, the position of the decoupling point provides interesting clues about how much "mass" the company has already put in mass customization. In other words, this point affects the portion of mass production within the system. The third functional requirement: fast delivery also depends on all design parameters. In effect, the position of the decoupling point influences the lead time required to build the customized product. On the other hand, the degree to which the production is smoothly running depends on the frequency of setups and the level of work-in-process inventories. This has in turn important effects on lead times. Finally, there is straightforward evidence that product variety contributes to slowing down production processes because of more frequent product changeovers.

$$\begin{cases} FR_1 = \text{Satisfy specific customer requirements} \\ FR_2 = \text{Produce economically} \\ FR_3 = \text{Deliver fast} \end{cases}$$

$$\begin{cases} DP_1 = \text{Product variety} \\ DP_2 = \text{Position of the decoupling point} \\ DP_3 = \text{Production flow} \end{cases}$$

$$\Rightarrow \quad \begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

Figure 3: Functional requirements and design parameters of a mass customization system

The design matrix for a typical mass customization system is provided by figure 3. It can be noticed that the system is a coupled one owing to nonzero elements above and under the diagonal line of the design matrix. In other words, the change of any design parameter affects more than one functional requirement. The problem with such a system is that management decisions about a functional requirement cannot be made independently of others. Therefore, this coupled system exhibits an imaginary complexity, which makes it not obvious in which sequence the functional requirements should be dealt with in order to optimize the system. In addition, such a system can trigger a time-dependent combinatorial complexity. In effect, for coupled systems, "…it may not be possible to introduce a functional period because reinitialization of the FRs will be difficult" (Suh 2005, p. 133). This means that the attempt to adapt to a small change in customer requirements not only induces a lost of efficiency but also a change in production flow. In the long run, this will not be advantageous because the system should be revised and perhaps redesigned each time a small change in customer requirements occurs.

Before going ahead with the analysis, it is useful to make the following observation: since the efficiency level and thus costs can usually be regarded as the result of strategic and/or operational decisions, it is more suitable to rearrange the design matrix, so as to put FR_2 (Produce economically) in the last row as it is depicted by figure 4. In this way, in the event that we succeed to decouple the system, costs will usually depend on the fulfillment of other functional requirements. To obtain a decoupled system, it is appropriate to make A_{12} and A_{32} tend to zero. Section 4 will discuss the variety management strategies that should be used in order to decouple the FRs of the system.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad \Longleftrightarrow \quad \begin{Bmatrix} FR_1 \\ FR_3 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & \boxed{\begin{matrix} A_{12} \\ A_{32} \end{matrix}} \\ A_{31} & A_{33} & \\ A_{21} & A_{23} & A_{22} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_3 \\ DP_2 \end{Bmatrix}$$

Figure 4: Appropriate rearrangement of the design matrix rows

Figure 5 sheds light on the variety-induced real complexity in mass customization. The total real complexity emerges because of uncertainties in fulfilling customer requirements, producing economically and delivering fast.

In the attempt to be more customer-oriented, the mass customizer is prone to satisfy a wider range of customer requirements over time. This adaptation to the customer needs, which may be planned in advance and sometimes unplanned, moves the current probability density of FR_1 to the left. In other words, the common range making up the surface of the overlapping area of the design and system ranges becomes larger. It is worth noting that the design range represents the set of requirements of all potential customers, while the system range is what the mass customizer can actually fulfill. In this case, real complexity of satisfying FR1 decreases because knowledge about customer requirements ameliorates. Nevertheless, a certain real complexity that cannot be avoided will usually exist. This complexity is mainly due to the difficulties encountered in order to identify the real customer requirements. This result has also been demonstrated by Blecker et al. (2005) who developed a customer needs' model for mass customization illustrating the discrepancies between real customer requirements and those requirements that the mass customizer can actually fulfill.

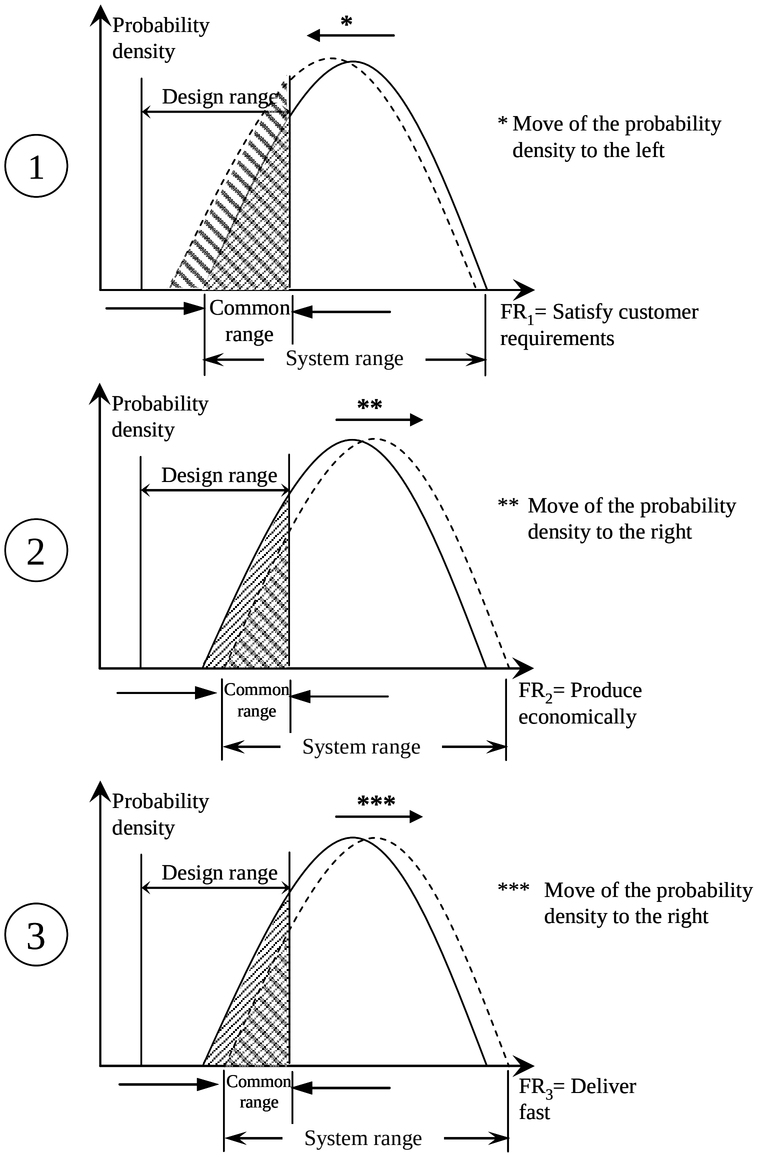

Figure 5: Illustration of the variety-induced real complexity by means of Suh's complexity theory for mass customization

Because mass customization induces a coupled system, any change in one FR adversely affects the fulfillment of other FRs. Thus, if the mass customizer strives to fulfill a larger spectrum of customer requirements (a shift of the density probability to the left), it is expected that the density probabilities of FR_2 (= Produce economically) and FR_3 (= Deliver fast) move to the opposite direction. Consequently, the corresponding common ranges will be smaller, thereby increasing time-independent real complexity and simultaneously inducing a time-dependent combinatorial complexity. The time-dependent combinatorial complexity can be explained as follows. As the mass customization system is constrained to handle more and more variety, the uncertainty of meeting costs and delivery goals increases. The system may evolve to a chaotic system that cannot be controlled anymore. In the following section, we will discuss the variety management strategies that have been developed thus far. Then, we will illustrate the potential of these strategies in reducing complexity on the basis of Suh's framework.

Variety Management Strategies

We distinguish between variety management strategies at the product level and at the process level. The strategies that can be used to manage variety at the product level are: component commonality, product modularity and platforms. Those implemented at the process level are: component families/cell manufacturing, process modularity, process commonality and delayed differentiation. It is noteworthy that although most variety management literature agues the potential of these strategies to reduce and/or avoid complexity (e.g. Wildemann, 2003); it is not obvious what kind of complexity they can cope with.

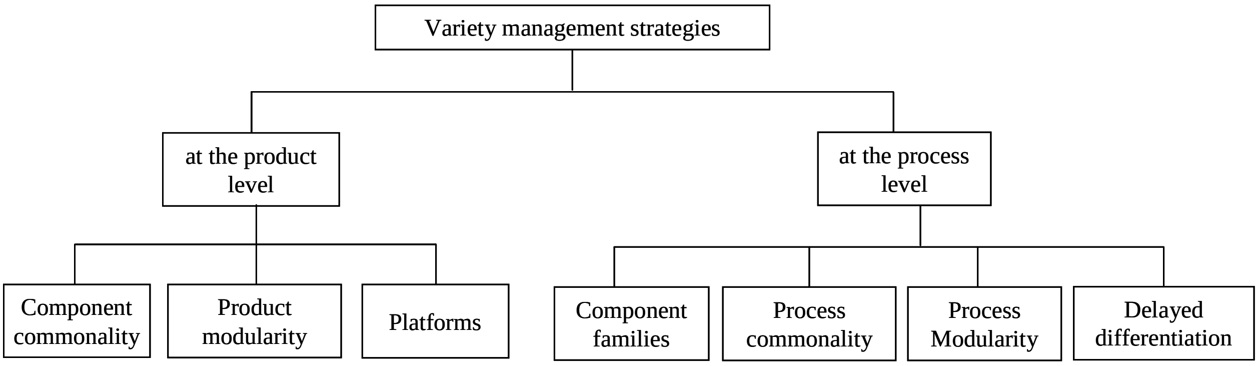

Figure 5: Variety management strategies at the product and process levels

At the Product Level

- Component Commonality

Commonality aims to use a few components in as many products as possible so long as it is economical. In effect, large product variety need not necessarily yield a large number of internal parts (e.g. Moskato, 1976). However, the attempt to increase commonality between products may result in over designed common components. Though such a functional congestion may incur additional direct costs, the benefits of fewer part variety and lower overheads may even be larger (Anderson, 2004). In addition, commonality enables risk pooling which leads to more accurate volume forecasts of the common component in stochastic demand environments.

- Product Modularity

Product modularity is an attribute of the product which characterizes the ability to mix and match independent and interchangeable product building blocks with standardized interfaces in order to create product variants. The one-to-one mapping between functional elements and physical building blocks is desirable. However, it refers to an extreme and ideal form of modularity that is generally difficult to achieve in practice (Blecker and Abdelkafi, 2006). Modularity "…allows the firm to minimize the physical changes required to achieve a functional change" (Ulrich and Eppinger, 2000, p. 187). It also enables the production of variety while facilitating the achievement of both economies of scale and scope (Pine, 1993).

- Platforms

A product platform can be described as a basic common module that is implemented in several variants of a product family. Platforms are cost-intensive and are developed to serve as the basic component for a long period of time. They support the concentration on core competencies, while decoupling the life cycles of the product family variations (Nilles, 2002).

At the Process Level
- Component Families

Grouping components into families is a variety management strategy that has been frequently discussed in connection with cellular manufacturing. Cellular manufacturing is a concept that has emerged from the group technology philosophy. It aims at grouping parts either with similar design features or manufacturing processes into part families. The main objective is to reduce the total setup time by decreasing the total number of changeovers (e.g. Yeh and Chu, 1991).

- Process Commonality

Process commonality reflects the degree to which products can be manufactured or assembled on the basis of a few number of processes. The number and diversity of processes give indications of the difficulty of planning and controlling internal production. Treleven and Wacker (1987) examine the relationships existing between process and component commonality. While component commonality necessarily increases process commonality, the reverse is not true since different component parts can be manufactured on the basis of a small number of processes.

- Process Modularity

Baldwin and Clark (2000) refer to modularity as the building of a complex system from smaller subsystems that can be designed independently yet function together as a whole. From this definition, it follows that process modularity consists in dividing a large process into smaller sub-processes that can be designed and carried out independently while still ensuring that the whole process fulfills its objectives. Swaminathan (2001, p. 128) provides a more general definition as he notes that "*modular process* is one where each product undergoes a discrete set of operations making it possible to store inventory in semi-finished form and where products differ from each other in terms of the subset of operations that are performed on them. Any discrete assembly process would classify as modular." Ericsson and Erixon (1999) relate product modularity to process modularity. They mention that modules can be manufactured and tested within independent and decoupled processes so as to decrease production lead times.

- Delayed Differentiation

Delayed product differentiation calls for the redesign of products and processes in order to delay the point at which product variations assume their unique identities. In this way, the process would not commit the work-in-process into a particular product until a later point (Lee and Tang, 1997).

Reducing Complexity in Mass Customization

First of all, it should be noticed that the mass customization system cannot be transformed to an uncoupled system with a diagonal design matrix. For instance, the endeavor to improve the alignment level with customer requirements will always affect the width and depth of the product portfolio, which influences in turn the costs' position of the firm. Thus, the correlation between FR_1 (= Satisfy customer requirements) and FR_2 (= Produce economically) can never be eliminated. However, it is possible to transform the system to a decoupled one by effectively implementing the variety management strategies that are discussed previously. Toward this aim, the mass customizer has to manage its processes so that A_{12} and A_{32} tend to zero. Recall that A_{12} refers to the correlation between the satisfaction of customer requirements and position of the decoupling point whereas A_{32} represents the relationship between the fast delivery requirement and position of the decoupling point. This further confirms the criticality of the decision concerning the placement of the decoupling point in order to effectively manage the mass customization system. Since the decoupling point is a design parameter affecting the production process, we shall explore in the following, the potential of variety management strategies identified *at the process level* in reducing complexity.

Critical elements Process strategies	$A_{12} \rightarrow 0$	$A_{32} \rightarrow 0$
Delayed differentiation	√	-
Process modularity	-	√
Process commonality	-	√
Component families	-	√

Figure 6: The effects of variety management strategies at the process level on design matrix elements A_{12} and A_{32}

The effects of the strategies at the process level on A_{12} and A_{32} are illustrated by figure 6. With Delayed differentiation, the dependency between the satisfaction of customer requirements and position of the decoupling point can be decreased. Note that the implementation of delayed differentiation need not necessarily imply the existence of a decoupling point within the production process and vice versa. In effect, delayed differentiation describes the strategy of letting product variants assume their unique identities at later process stages, whereas the decoupling point refers to the point from which the process switches form the push (lean) to the pull (agile) mode. Therefore, it is obvious that without delayed differentiation, high work-in-process inventories must be held at the decoupling point. However, if the point of differentiation is delayed as much as possible, the level of these inventories can be considerably reduced. In addition, delayed differentiation can be applied in both forecast- and order-driven production systems (Pil/Holweg, 2004); whereas the presence of a decoupling point necessarily means that a part of the production system is driven by customers. A high dependency between customer requirements and the decoupling point means that an increase of the degree of customization necessarily triggers a backward movement of the decoupling point. But an adequate implementation of delayed differentiation reduces this dependency in that only downstream activities will be affected, whereas upstream processes which are placed prior to the decoupling point are kept unchanged. As a result, the strategy increases the stability of production and considerably reduces the uncertainty in achieving efficient production and realizing fast deliveries.

Depending on the industrial context, delayed differentiation can be achieved through: (1) component commonality at the first stages of the production process, (2) operations reversal (Lee and Tang, 1997), or the use of so-called vanilla boxes (Swaminathan and Tayur, 1998). With commonality at early manufacturing steps, the benefits of risk pooling can be attained (Eynan and Fouque, 2003). In effect, within a certain planning period, it is more accurate to forecast the aggregate demand for the common component than the single demands of many different components (Sheffi 2005). The second concept of operations reversal which has been studied quantitatively by Lee and Tang (1997) consists in redesigning the process and/or products in such a manner that the sequence of production processes is reversed. This approach has been implemented with success in the apparel industry by Benetton. Instead of dyeing and subsequently knitting garments, Benetton restructured its production process, so that the dyeing sub-process which is crucial for the satisfaction of customer requirements but with the shortest lead time and smallest value added has been placed at later stages. Using this strategy, Benetton could improve its responsiveness to customer preferences and increase efficiency. In contrast to commonality and operations reversal, the vanilla boxes approach does not involve a redesign of products or the process. It only consists in preassembling some components on a push basis, so that the final product variants will no longer be assembled from scratch when the customer order arrives.

It can be concluded that delayed differentiation leads to deterministic costs and deterministic lead times in the upstream activities that precede the decoupling point, regardless of what product variants are ordered by customers. It reduces the uncertainty in achieving efficient production and fast delivery without affecting the extent of customer choice. Therefore, it can be stated that delayed differentiation diminishes the real complexity of the mass customization system. On the other hand, as previously stated, the strategy makes it possible to adapt the mass customization production system over time by adjusting the processes in the pull system while keeping the push system unchanged. Consequently, delayed differentiation transforms time-dependent combinatorial complexity into a periodic complexity. However, without delayed differentiation, combinatorial complexity emerges, thereby triggering gradual movement of the decoupling point to earlier stages in the production system. This may lead to the degradation of the costs’ position and delivery lead time of the mass customization system.

While delayed differentiation reduces the dependency level between customer requirements and the position of the decoupling point, component families, process modularity and process commonality seem to make the fast delivery requirement less sensitive to the placement of the decoupling point. Furthermore, whereas delayed differentiation influences the whole system, the other strategies can be implemented to redesign and manage the process in each subsystem apart. For example, one can implement the process modularity strategy in both the push and pull subsystems.

Making the fast delivery requirement less dependent on the decoupling point position means that no matter where the decoupling point is placed, short delivery times can be usually ensured. Olhager (2003, p. 325) also comments on the independence between the decoupling point and delivery time as he mentions that "[t]he reduction of lead times for downstream activities will reduce the delivery lead time (…), but will not change the OPP[1] with respect to the material flow in the product structure per se." In this context, it is important to note that the delivery time acceptable by customers is a requirement which is relative to the mass customization environment in question. It is straightforward that customers who request design changes (e.g. in investment goods such as specific tool machines) would be willing to wait longer for delivery than those who configure their products on the basis of standard components and subassemblies (e.g. a computer). Thus as the mass customizer strives to increase the alignment of the product portfolio with customers' requirements, the decoupling point may move upstream away from its current/ideal position. In this case, longer delivery times would be an unavoidable consequence, which may adversely affects the performance of the mass customization system. With an adequate use of process commonality, process modularity and component families, the fast delivery requirement can be made less dependent on the position of the decoupling point. In effect, these strategies not only improve production efficiency (e.g. changeover cost reduction), but also increase the velocity of manufacturing. For instance, Ericsson/Erixon (1999) mention that process modularity enables one to adapt the product modules in specific module areas on the shop floor, without considerably affecting delivery times. All three strategies decrease real complexity with respect to the functional requirements: FR_2 = produce economically and FR_3 = deliver fast. Process modularity has an additional potential in that it enables the reduction of combinatorial complexity because it divides the whole process into independent smaller sub-processes. However, process commonality and component families are not capable of transforming the time-dependent combinatorial complexity into a periodic complexity. As manufacturing cells/common processes have to handle larger variety, their performances get worse due to the difficulties of planning and scheduling. For instance, Kekre (1987) demonstrates through a simulation analysis that the diversity of parts increases the queuing delays and optimal batch sizes in manufacturing cells, thereby triggering larger lead times of manufacture and higher work-in-process inventories. In the right upper part of figure 7, the potential of variety management strategies at the process level to reduce complexity are presented.

The strategies at the process level may call for design changes in the product. The left upper part of figure 7 summarizes the relationships between the variety management strategies identified at both levels. Product platforms necessarily improve process modularity, process commonality, and support delayed differentiation. In fact, the design of products around platforms can even be regarded as a sufficient condition for the implementation of delayed differentiation (Nilles, 2002). Since the delay of the differentiation point reduces real complexity and transforms combinatorial complexity to periodic complexity, it can be stated that product platforms are capable of influencing complexity in the same way. On the other hand, product modularity to a great extent supports the achievement of the modularity of processes. In effect, product modules can be manufactured and tested in independent process modules. Therefore, in a mass customization system, product modularity also contributes to the management of real and combinatorial complexities. Furthermore, product modularity improves process commonality and supports the strategy of component families. This can be

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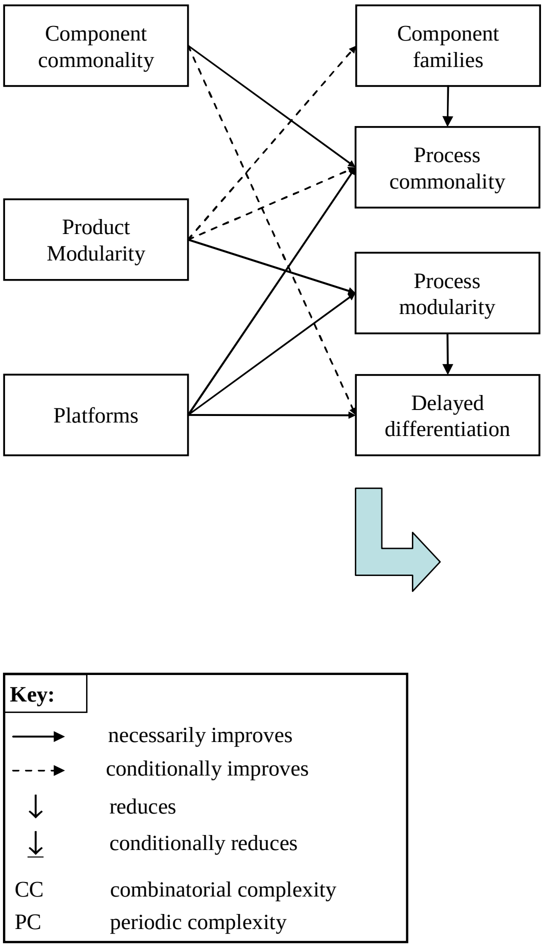
[1] OPP means "Order Penetration Point" which is a synonym for the "Decoupling Point".

attained if different module variants can be processed within the same module area on the shop floor while involving less frequent and shorter setups. Finally, component commonality necessarily improves process commonality (Treleven and Wacker, 1987), thereby reducing the real complexities of delivering fast and producing economically. It is worth noting that commonality supports delayed differentiation only if the common components are a part of the product platform. As a result, component commonality conditionally improves delayed differentiation. The results with respect to the variety management strategies at the product level are presented in the right lower part of figure 7.



Potential of the variety management strategies at the process level to reduce complexity

Strategy \ Complexity type	Imaginary complexity	Real complexity	Transformation of CC to PC
Component families	↓	↓	-
Process commonality	↓	↓	-
Process modularity	↓	↓	↓
Delayed differentiation	↓	↓	↓

Potential of the variety management strategies at the product level to reduce complexity

Strategy \ Complexity type	Imaginary complexity	Real complexity	Transformation of CC to PC
Component commonality	↓	↓	$\underline{\downarrow}$
Product modularity	↓	↓	↓
Platforms	↓	↓	↓

Figure 7: The relationships between variety management strategies at the process and product levels and their potentials to reduce complexity

From the discussion presented earlier, it is obvious that the variety management strategies have unequal potentials to reduce complexity within a mass customization environment. The strategies with the lowest levels of complexity reduction are: component families, component commonality, and process commonality. These strategies contribute to the management of the imaginary and real complexities according to Suh's framework. Product modularity, platforms, process modularity and delayed differentiation have higher potentials because they additionally transform the combinatorial complexity into a periodic complexity. It is also legitimate to assume that the strategies with the lowest level of complexity reduction should be implemented first, followed by the strategies with superior capabilities. This suggests that there is a sequence according to which variety management strategies should be applied in the practice. The logical sequence for the implementation of a complexity-based variety management is depicted by figure 8. Component families are the starting point of the framework. Building component families is nothing else than grouping existing components into clusters, e.g. based on geometrical similarities so as to reduce setup times and thus production lead times. This strategy may not call for extensive engineering efforts as component commonality. Therefore, component commonality has to be considered in a second step after having grouped component parts into families. Since process commonality largely benefits from prior implementation of component families and commonality (see figure 7), this strategy should be put at the third place. Consequently, we derive the application sequence of variety management strategies with low potential of complexity reduction: component families → component commonality → process commonality. At this stage, it is important to note that companies which have successfully implemented these strategies will not be able to achieve mass customization efficiently. Over time, the arising combinatorial complexity will negatively affect the performance of the mass customization system with respect to fast deliveries and efficient production.

Regarding the variety management strategies with higher potentials of complexity reduction, it should be noticed at first that product modularity is the key for the achievement of process modularity, product platforms and delayed differentiation. Product modularity may call for the redesign of the product with the objective to standardize the module interfaces and also to minimize the interactions between the product building blocks. Therefore, product modularity is the fourth step within the implementation sequence of the complexity-based variety management. In addition, as aforementioned, product modularity is an enabler of process modularity on the shop floor, in that modules can be manufactured or assembled in independent module areas. Consequently, the fifth step is the application of process modularity. The resulting sequence until now is the following: component families → component commonality → process commonality → product modularity → process modularity. We call this sequence: the minimum variety management sequence for an efficient and effective implementation of mass customization. Mass customizers that adequately implement these strategies may be successful, but they must be aware that they did not completely discard the negative effects of combinatorial complexity. This complexity still arises because the mass customization system is still a coupled one due to $A_{12} \neq 0$. A case study from the practice that illustrates this issue has been provided by Aasland et al. (2001). The company in question is Norema which is based in Oslo, Norway. It is a manufacturer of customized kitchen interiors that uses a planned, structured and modularized product program. The authors reported that in spite of appropriate modularity in the product and production facilities, the product program "…has developed and expanded over the years into *an unmanageable number of production variants*" (p. 45) with an enormous variety of elements. In fact, our model based on Suh's theory predicts these deficiencies and even provides an explanation for the problem. It states that the performance of such a mass customization system will deteriorate over time because of combinatorial complexity that is mainly triggered by the high dependency between customer requirements and the position of the decoupling point. To avoid this problem, the application of product platforms and delayed differentiation is necessary. In fact, the efforts for the standardization of product and process modules should lead to a platform strategy. In this context, Aasland et al. (2001, p. 43) mention that "[p]latform building depends on modularisation. In many ways you can say that platform building is a successor to a modular product program, that gives even more commonality between the different models, and thus efficiency." Furthermore, in the business administration literature, many authors (e.g. Piller and Waringer, 1999) recommend to consider not only the product but also the process perspective when embarking on a platform strategy. That is why, product platforms should be applied after having implemented product and process modularity. The last step of the implementation of a complexity-based variety management for mass customization is delayed differentiation. The main enablers for delayed differentiation can be platform strategies through the increase of commonality at the first process stages and/or process modularity with the objective to make operations reversal possible.

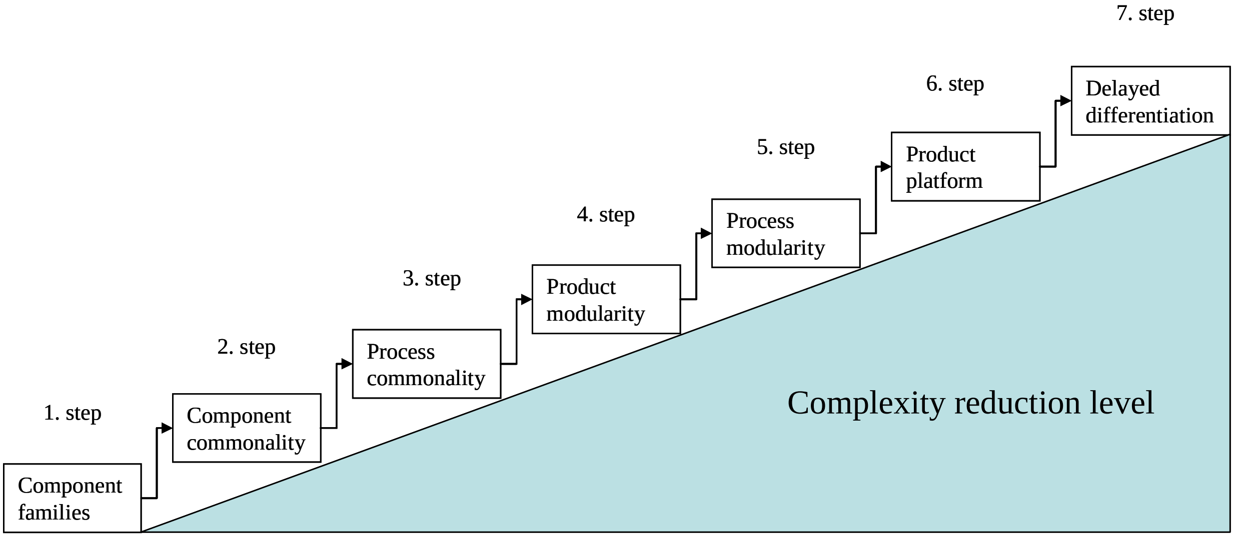


Figure 8: The logical sequence for the implementation of a complexity-based variety management for mass customization

Conclusions

This paper considers mass customization from the perspective of Suh’s complexity theory. This theory abandons the idea of complexity as an absolute measure and defines it relative to what should be achieved or known. Within this framework, complexity consists of time-dependent and time-independent complexities. Time-independent complexity can be divided into real and imaginary complexities, whereas time-dependent complexity may be divided into combinatorial and periodic complexities. To apply this theory, the mass customization system is examined with respect to its fundamental functional requirements, which are: the satisfaction of customer requirements, economic production, and fast delivery. To achieve these functional requirements, three design parameters are identified, namely: product variety, position of the decoupling point and production flow. The analysis of the design matrix which relates the functional requirements to design parameters has revealed that the mass customization system is a coupled system. This demonstrates the system complexity on the one hand and unveils the main complexity origins on the other hand. Complexity represents the uncertainty in satisfying customer requirements, producing economically and delivering in a fast-paced manner.

The mass customization system cannot be transformed to an uncoupled system. Through a goal-oriented use of variety management strategies, it is however, possible to transform the system to a decoupled one. To achieve this goal, managers should strive to implement the following recommendations:

- Decreasing the dependency between the satisfaction of customer requirements and position of the decoupling point by exploiting delayed differentiation and platform strategies.

- Making delivery time less dependent on the position of the decoupling point by modularizing products and processes, increasing the commonality between products, implementing fewer processes on the shop floor with low setup times, and implementing group technology.
- Implementation of the variety management strategies in an ascending order of complexity reduction level

If these recommendations are satisfied in a mass customization system, complexity can be strongly reduced and kept under control. In fact, dealing with variety-induced complexity is the main challenge that should be faced in order to lead the strategy to success. It also has been shown that the mere application of modular structures do not switch off some complexity problems that can arise during the pursuit of the strategy.

However, our discussion has some limitations. In this paper, we dealt with complexity in mass customization from a conceptual perspective. Therefore, a case study from the practice with the attempt to apply the developed ideas can provide additional insights concerning the variety-induced complexity in mass customization. In the presence of a case study, the design matrix and thus the degree of coupling of the mass customization system can be examined more accurately. For instance, it can be evaluated as to how the position of the decoupling point moves as new customer requirements are introduced and fulfilled by the system. To do this, it is necessary to measure the placement of the decoupling point and to evaluate customer requirements. In this context, Olhager (2003) proposes the ratio: Production time divided by delivery time, as a measure for the evaluation of the position of the decoupling point. On the other hand, the degree of satisfaction of customer requirements can be estimated as the ratio of the number of product attributes actually fulfilled by the mass customizer to the number of attributes that customers would be interested in. Furthermore, it should be noted that there are many degrees of product modularity. Whereas the degree of modularity in certain industries is very high (e.g. computer industry), in other industries, the degree of products is much lower (e.g. automotive industry). Therefore, an interesting area for further research is to examine the complexity reduction level (especially combinatorial complexity) as a function of the degree of modularity of products.

Another direction for future research may be to use quantitative models in order to evaluate the complexity of a mass customization system. It can be useful to examine the sensitivity of an eventual measure of complexity with respect to variety. In fact, our future work will be driven by the thesis that the complexity of a mass customization system will be less sensitive to variety if this variety moves under a certain limit level. However, after transgressing this limit, complexity will increase exponentially, which makes the system unpredictable and difficult to manage. Therefore, simulation techniques coupled with the use of complexity measures are appropriate instruments to determine the optimal product variety that can be handled by a specific mass customization system.

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