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MASS CUSTOMIZATION VS. COMPLEXITY: A GORDIAN KNOT?

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Abstract:

Mass customization is a business strategy that aims at satisfying individual customer needs, nearly with mass production efficiency. It induces a high complexity level because of various customer requirements and a steadily changing environment. However, mass customization has some potential to reduce complexity. These interdependencies between mass customization and complexity form a Gordian knot that should be cut in order to point out that mass customization is not just an oxymoron linking two opposite production concepts, but a business strategy that contributes towards reaching a competitive advantage. On the one hand, mass customization increases the production program, manufacturing and configuration complexities. On the other hand, mass customization can contribute to reduce complexity at the levels of order taking process, product and inventories. The main results attained through the analysis are integrated in a comprehensive framework that shows the complexity increasing and complexity decreasing aspects due to mass customization.

Introduction

Mass Customization links two production concepts that look at first glance to be opposites, namely mass production and customization. Whereas mass production strives for offering standard products to a mass market at low costs by drawing the economies of scale benefits, mass customization aims at satisfying individual customers' needs with a comparable efficiency. The main objective is that "…nearly everyone finds exactly what they want" (Pine, 1993) at an affordable price that does not considerably deviate from the price of a corresponding standard product. So, mass customization strategy concentrates on both dimensions which are decisive in order to create a competitive advantage, namely quality and costs. In this context, quality not only means to be in conformance to specifications, but also to ensure customer satisfaction and value.

In such a production environment, a close customer-supplier relationship is decisive to give customers the possibility to express their specific requirements which are then translated into product-specific descriptions for manufacturing. In addition, the information which arises

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during the interaction process can be used in order to build up a long-lasting individual customer relationship (Piller, 2001).

The strategic benefits of mass customization have been widely discussed in the theory of business management. However, large deficits coin the practical application (Piller/Reichwald, 2002). Moving to and practicing mass customization is a very difficult task. The principal reason that is ascribed to the failure of some mass customization projects is the increasing complexity problem. Research that examines complexity in the specific case of customization is still missing. Up to now, it is very common that one extrapolates the findings and results on variety and complexity studies that are achieved in batch or even mass production in order to point out the effects of complexity in mass customization. This point of view is not correct because mass customization has some particularities that should be taken into account when dealing with the complexity issue.

In this paper, we will analyze the existing interdependencies between mass customization and complexity. In the next section, we will give a short literature review on complexity in business administration. Section 3 examines how mass customization can induce complexity in operations and manufacturing-related tasks. Section 4 provides another perspective when dealing with complexity in mass customization. It will be shown that the mass customization paradigm can contribute to a reduction in complexity within organizations. Section 5 summarizes the attained results in both sections 3 and 4 and provides a comprehensive framework enabling one to better understand the levers that can induce or reduce complexity in mass customization. Section 6 concludes and points out some research directions.

Complexity: A Short Literature Review

Until now, the term complexity has no satisfactory and generally admitted definition. It is basically discussed in connection with the system theory and is referred to as a system attribute. A system consists of elements or parts (objects, systems of lower order, subsystems) and the existing relationships between them. It is also agreed that a system should perform a specific function and has to be well distinguished from its environment without confusion. The complexity of a system is defined with respect to the complexity variables, namely number, dissimilitude and states' variety of the system elements and relationships. These variables enable one to make the distinction between static and dynamic complexity. Whereas static complexity describes the system structure at a defined point in time, dynamic complexity represents the change of system configuration in the course of time. For example, by considering the product arrangement system which consists of the functional and building oriented subsystems of the production program (Nilles, 2002), all possible product variants that can be manufactured at a point in time determine the static system complexity. However, the dynamic complexity is determined by the frequency and magnitude of changes of the product arrangement system when new product variants are introduced or eliminated. On the basis of the structural and dynamic complexities, Ulrich/Probst (1988) have determined a taxonomy for system complexity. When both complexities are low, then the system is simple. In the case of a high (low) structural complexity and low (high) dynamic complexity, the system is considered to be complicated (relatively complex). When both complexities are high, then the system is said to be extremely complex.

Saeed/Young (1998) define complexity in business administration as the "…systemic effect that numerous products, customers, markets, processes, parts, and organizational entities have on activities, overhead structures, and information flows." The main problem triggered by much complexity is the hidden costs. The costs of complexity are generally not visible and can badly affect the competitive advantage of the enterprise. Mass customization triggers high complexity because of the variety of products, markets ("Markets of one"), processes, customers, etc. The mass customizing system cannot be a simple one owing to the complexity of its environment. This is in according with Ashby's law of requisite variety in the cybernetics, which says that "variety can destroy variety" (Ashby, 1957, p. 207) and can be also extended to "complexity can destroy complexity". But the problem remains to determine how much complexity is optimal. Saeed/Young (1998) propose to identify the complexity the customer rewards and the complexity the market is not willing to pay. Frizelle/Efstathiou (2002) also makes such a distinction and call the former "good complexity" and the latter "bad complexity".

In order to cope with complexity, Wildemann (2000) makes the distinction between three measures to be taken, which are: complexity reduction, complexity prevention and complexity control. Complexity reduction aims at simplifying structures for the short term by e.g. eliminating unprofitable product variants or reducing the customer system elements. Complexity prevention is targeted towards e.g. developing methods capable of assessing complexity, for instance costs of variety. Complexity control deals with the rest of complexity that cannot be reduced because of environmental complexity such as the diversity of market requirements. To manage complexity, McKinsey prefers to distinguish between instruments for the reduction of program, product and process complexities (Maroni, 2001). Other authors (e.g. Reiss, 1992; Hoege, 1995) differentiate between complexity decreasing and complexity increasing measures. Bliss (2000) has developed an integrated four phases concept for the management of complexity, which is based on a system theoretical analysis. The first step is to eliminate the autonomous enterprise complexity. This means to cut internal complexity inside the enterprise that has no correspondence in the environment and subsequently represents a congestion of the Ashby's law of requisite variety. The objective of the second step is to reduce the correlation between internal and external complexities. The basic target is to make internal complexity less vulnerable to environmental changes. The third step deals with a conscious reduction of the perceived market complexity by simplifying e.g. the production program. The fourth step is targeted towards complexity control by e.g. modularizing manufacturing. The relevance of the work of Bliss (2000) is the determination of a sequence according to which complexity management concepts should be applied.

In the technical literature, there are several approaches to manage complexity. These are in some cases contradictions, which emphasize the strong subjectivity when coping with complexity problems. But until now there is very little work that relates to the development of measures or metrics for an objective assessment of complexity. This may be due to the failure and lack of adaptability of many complexity measurements that are suggested in the complexity theory. However, Frizelle/Woodcock (1995) devise an entropic measurement for evaluating complexity in manufacturing. Entropy is well known in thermodynamics and in the information theory. It provides a measure of the amount of information associated with the occurrence of given states. This measurement, successfully applied in practical manufacturing cases, suggests that complexity reduction can be achieved when there are fewer processes, fewer states as well as fewer variations of states. Furthermore, it is relevant to point out the work of Blecker et al. (2003) in the specific field of mass customization. On the basis of a sub-process model that contains the product configuration, the development, purchasing, production, logistics and information sub-processes, Blecker et al. assign performance parameters to each sub-process. Then, complexity key metrics are assigned to each performance parameter. Subsequently, all key metrics are presented in a comprehensive model that enables one to understand the mutual relationships between the different metrics.

However, this model consists of key metrics that indirectly permit one to assess complexity inside a mass customizing system. They do not represent direct measurements of complexity.

In this paper we do not strive to develop a concept for complexity management in mass customization or measurements for complexity assessment. The main goal is to cut the Gordian knot between complexity and mass customization. As aforementioned, we will put some clarifications not only on the causes of complexity in mass customization, but also on the potential of mass customization to reduce complexity. In the following, we will focus our complexity analysis on the main system in mass customization (Figure 1). It contains three subsystems, namely the product configuration system, manufacturing system and product arrangement system. We are convinced that this system is the most complex one that has to be optimized in a mass customizing enterprise. The product configuration system is a software tool that elicits customers' requirements. We make the distinction between the front end and the back end systems. Whereas the front end system is the user interface, the back end system contains the product logic which means the product structure. The manufacturing system is required to produce individualized goods with near mass production efficiency. That is why, it is legitimate to make the distinction between mass production and customization systems. Moreover, as aforementioned the product arrangement system contains the functional and the building-oriented systems. The functional system has a relevant importance from customers' perspective because customers generally express their needs in terms of requirements, whereas the building-oriented system has a technical relevance and enables one to map functional requirements into product-oriented description. Furthermore, it is important to point out that there are mutual relationships between the different specified systems.

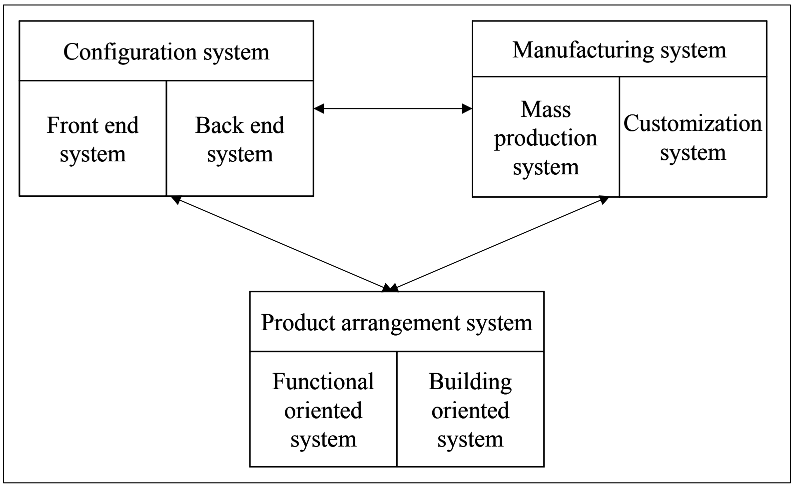

Figure 1: The system to be optimized in mass customization

Increasing Complexity Due to Mass Customization

Mass Customization Triggers High Production Program Complexity

The production program consists of all products that are manufactured in the enterprise. In this context, one should make the distinction from the product program which contains not only the manufactured products (i.e. the production program), but also the end products to be sold without being processed (goods for resale). In mass customization, the involved production program is generally characterized by a very high variety. For example, Cmax.com, a mass customizer of sports shoes offers approximately $3*10^{21}$ variants over the Internet. The entire surface of the earth would scarcely suffice for exhibiting all of the possible variants of shoes (Piller et al., 2003). Additionally, many examples of mass customizers from the automobile industry show that the number of product variants has considerably increased in the last years (Piller, 2001).

To illustrate the rapid proliferation of variety, Rosenberg (1996) shows with a simple example how total number of product variants that is manufactured on the basis of 9 must-modules and 14 can-modules can go up to the billions. An empirical study of Wildemann (2001) has shown that with the doubling of the number of product variants in the production program, the unit costs would increase about 20-35% for firms with traditional manufacturing systems. For segmented and flexible automated plants, the unit costs would increase about 10-15%. Wildemann concluded that an increase of product variety is associated with an inverted learning curve. This a priori implies that mass customization hardly leads to ensure a competitive advantage because of high variety which is driven by strong product differentiation. This problem is also complicated by the fact that customers no longer accept any prices even when receiving individualized goods. Moreover, many studies have confirmed that manufacturing enterprises with a narrow production program are more successful than those with broader range of product variety.

Variety-induced complexity triggers higher costs which arise in the form of overheads (Anderson, 1997; Rosenberg, 2002). In addition, even by applying some modern cost calculation concepts such as activity-based-costing, it is generally very difficult to adequately and fairly allocate these indirect costs to the corresponding product variants. This has driven e.g. Martin/Ishii (1996) to develop metrics, namely commonality, setup and differentiation indexes to capture complexity costs. However, they have stated without proof that complexity costs would be a linear function of these three indexes. This further confirms the difficulty to objectively quantify the complexity.

Because of a high individualization level in mass customization, Anderson (1997) points out that customers' needs should be mapped to a product family instead of a single product. This means that design engineers have to create flexible product structures which enable customers to individually configure their product variants. This goal can be achieved by developing products around modular structures and platforms. Modules are structurally independent building blocks that perform specific functions and have well-defined interfaces to other modules. However, a platform consists of one or several modules with a high commonality level. But the development of such product architectures is very time-consuming and cost-intensive. A main problem is to specify the module or platform interfaces. The number and the variety of interactions between modules in the building-oriented system of the product arrangement system may increase the production program complexity.

Mass Customization Triggers High Manufacturing Complexity

In the technical literature, several concepts are identified to be suitable for the implementation of the mass customization strategy. Following previous work of e.g. Duray et al. (2000), Piller (2001) and Mchunu et al. (2003), we retain five main concepts that represent a continuum from mass production to pure customization and involve different levels of customer integration and manufacturing complexity (Figure 2). The concept of adaptive products is characterized by the lowest level of process complexity and is based on standard products individualized by customers themselves. The value adding retailers approach also relies on standard products which are ex post adapted by the retailer to a customer's requirements. In the assemble-to-order approach, customers configure their product variants on the basis of standard modules. However, the fabricate-to-order approach involves a higher level of customization and also complexity than the assemble-to-order because customers are allowed to introduce changes on modules within a defined scope. Finally, pure customization presents the highest level of customization because parts or modules are engineered according to customers' needs. Pure customization as a mass customization strategy obligatorily involves a mass production process and should not be confused with job-shop production where the whole product is engineered according to the customers' requirements.

Adaptive products and value-adding retailers concepts are based on standard products. They involve a mass production system with low complexity level. However, all other mass customization approaches are characterized with a high product variety. Tseng/Jiao (2001) point out that increasing product variety in mass customization triggers a main challenge in manufacturing that is to efficiently plan and control production. In such an environment, PPC systems such as MRPII (Manufacturing Resource Planning) or ERP (Enterprise Resource Planning) that are originally designed to support manufacturing in operations with a limited number of product variants, are not efficient. The main encountered problems basically lie in the necessity to specify all possible product variants in the system.

Furthermore, mass customization requires flexible manufacturing systems on the shop floor. With such systems, it is possible to manufacture a high product variety in little batch sizes at relatively low costs. Although flexible manufacturing systems with flexible alternative machines, operation sequences and routings lead to potential improvements in the manufacturing system performance, they involve significant increases in the size of the production planning problem. Byrne/Chutima (1997) point out that an added degree of freedom due to manufacturing flexibility enormously increases the complexity of the structure of the scheduling function. Thus, flexible manufacturing systems for mass customization do not entirely solve the problem caused by variety because of high planning and scheduling complexity.

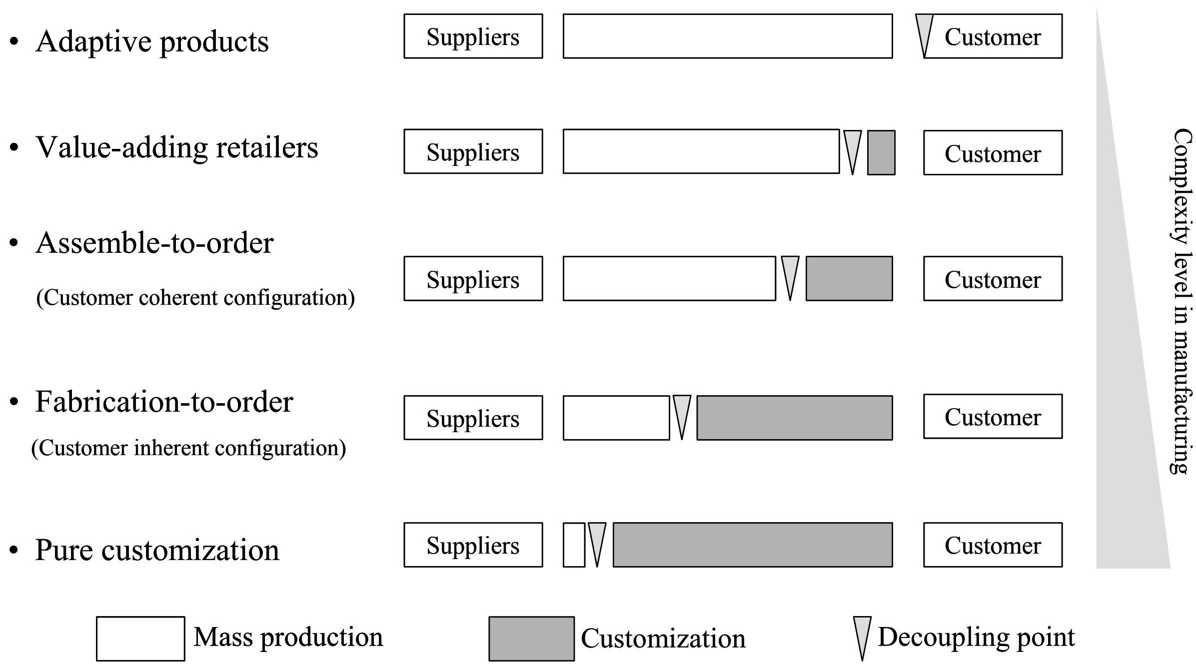

Figure 2: Mass customization concepts and their complexity levels

Mass Customization Triggers High Configuration Complexity

In opposition to the mass production system, where the manufacturer tells customers what they buy, mass customization assumes that consumers tell the manufacturer what to produce (Tseng/Jiao, 2001). Furthermore, in the technical literature the customer is considered as a “prosumer”, “co-producer” as well as “co-designer”. This points out that in mass customization, the enterprise system should not only involve the internal value adding system as it is common from a traditional view, but also the customer system (Figure 3). The traditional view would be satisfactory in business environments where customers do not undertake an active role in the value chain. The mass customization view considering the internal value adding and the customer systems is of high relevance when dealing with the complexity issue.

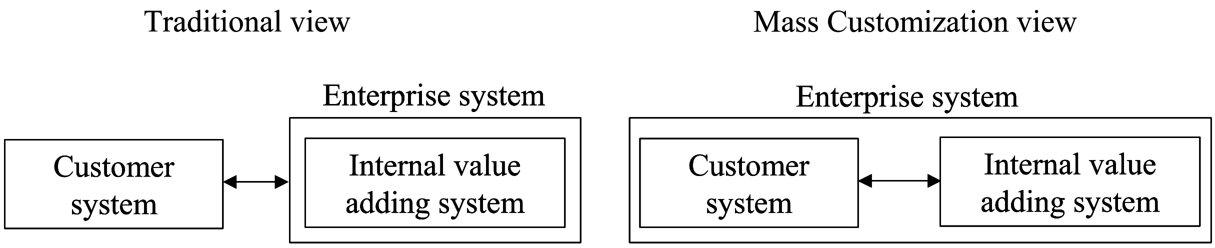

Figure 3: The enterprise system from a traditional view and a mass customization view

In mass customization, it is common that manufacturers use online configuration systems over the internet in order to enable customers to express their needs. von Hippel (2001) speaks of innovation toolkits with which customers have the possibility to innovate by self-designing products. The customer system has to be strongly considered when dealing with the configuration process because when product variety is high and reaches an astronomical scale, customers have difficulties to make a decision between product variants. They generally feel lost in huge product assortments and are overwhelmed by the configuration task. This aspect is called configuration complexity. Huffman/Kahn (1998) compared the attribute-based and the alternative-based presentations of product variants and found out that customers can better discover their preferences thanks to an attribute-based presentation. This confirms that the configuration complexity depends on the features of the software tool used for supporting customers. Piller et al. (2003) point out that because of large variety, customers are overloaded with information, which can result in configuration processes that take a long time. Moreover, increasing uncertainty may lead customers to an unwanted behavior that is to abort configuration and go away. To further explain the complexity of the decision making process during self-configuration, Blecker et al. (2003) speak about the objective and the subjective customers’ needs. They define the objective needs as the real needs perceived by a fictive neutral perspective and the subjective needs as the individually realized and articulated requirements. Whereas the fulfillment of the objective needs would lead to an optimal choice that actually satisfies customers’ needs, the subjective needs would only yield a suboptimal choice. Furthermore, customers may have the tendency to purchase products that do not optimally correspond to their requirements when they have to select a suitable variant from a product assortment characterized by high variety.

Decreasing Complexity Due to Mass Customization

Although mass customization involves increasing complexity at many levels, it has some potential to reduce complexity within the enterprise system. It should be shown that mass customization is not just a theoretical oxymoron linking two opposite production concepts, but a business strategy with a great ability to efficiently contribute towards providing manufacturers with a competitive advantage. Indeed, mass customization involves a very specific business environment. Customers no longer have a passive role in the value chain and are able to provide valuable, direct input. The implementation of product configuration systems enables one to reduce the order taking process complexity. Furthermore, it is not necessary to hold final products' inventory because products are not manufactured until the customer's order arrives. In addition, product complexity is reduced by standardization and modularization.

Mass Customization Reduces the Order Taking Process Complexity

The wide implementation of product configuration systems in mass customization provides customers with the possibility to configure their products according to their requirements and to send their orders per mouse-click to the manufacturer who can begin the production. The front end system of the product configurator interacts with the customer in order to elicit his needs. Customers can also visualize their choices and change them according to their requirements. The back end system of the configurator contains the product logic and does not tolerate inconsistencies between parts or modules, which ensures that the product ordered by the customer is able to be manufactured. Forza/Salvador (2002) point out that errors during order acquisition can be considerably reduced with the introduction of product configuration systems. Product variant prices as well as delivery point in times can be also automatically calculated. Thereby, sales personal can be enormously reduced because of the direct interaction between customers and supplier.

The integration of the configuration system with e.g. the product data management (PDM) system and the ERP system provides additional advantages. Product documentation with respect to involved parts or modules and routings can be automatically and efficiently generated. Product configuration systems generally do not attribute a different part number to each product variant. This would induce an explosion of data because of the possible variety of customers' orders. Therefore, configurators use a generic product structure that enables one to efficiently represent product data by avoiding redundancies (Tseng/Jiao, 2001).

Mass Customization Reduces Product Complexity

In order to be able to offer short delivery times and to benefit from the economies of scale and scope, modular product design is a very relevant issue in mass customization (Pine, 1993). Although modular architectures may induce some complexity during the design task, especially with respect to the specification of interfaces, they are decisive to make mass customization efficiently work. Modular product architectures can be considered as the basic enabler for mass customization. For instance, Piller (2001) ascribes the development of mass customization to the advances realized in the field of modular designs. Furthermore, it is noteworthy that product modularity does not necessarily imply that the supplier pursues mass customization. For example, some automobile manufacturers produce cars around modular architectures but still receive orders from retailers who do not imperatively involve specific customers' requirements. From this point of view, modularity is just an enabler for mass customization.

Inversely, according to the manufacturing system definition given above, mass customization should involve a mass production system. For this reason, the product has to be designed in such a way that mass production is possible, which can be optimally realized by developing modular architectures. That is why, in our opinion, mass customization in the context of make-to-order which excludes adaptive products' and value-adding retailers' approaches even obligatorily premises modular designs. Thus, mass customization implies modularity, which means a reduction of product complexity. So, modules can be manufactured independently from customer orders within a mass production system. After customers specify their requirements, modules are assembled together into product variants within the scope of the customization process. The concept behind this organizational approach made possible by modular designs is called postponement (e.g. van Hoek, 2001) that means to delay some activities in manufacturing until customer orders are received.

The main advantage of modular product architectures is to reduce product complexity by maintaining large end product variety. By opting for an integral architecture instead of a modular design, the potential to manufacture billions of product variants as it is common in mass customization would mean to design billions of different variants. Ulrich (1995) points out that a fully integral design requires changes to every component in order to be able to effect change in any single functional element of the product. However, modular structures enable one to manufacture a high range of variety on the basis of only few modules. Furthermore, modules increase the commonality level between products, which improves manufacturing performance. In addition, mass customization makes designers strive for increasing components commonality in- and between different modules.

Due to decoupled interfaces, a modular product architecture enables one to change certain modules for e.g. an upgrade without having to change the surrounding modules. Moreover, in contrast to an integral architecture, a modular design does not necessarily assume flexible component production equipments in order to efficiently achieve a high range of product variety. Another positive aspect of product modularity is to allow a better exploitation of supplier capabilities (Ulrich, 1995).

Mass Customization Reduces Inventory's Complexity

Classical mass production is based on requirements' forecasting, which generally means high inventories because of "product-push". However, mass customization reposes on a "customer-pull" strategy with the main advantage that production does not begin until customer order arrives (Piller, 2001). The result is that end product inventories are no longer required and the corresponding inventory costs are avoided. Industrial sectors that suffer from high customer demand fluctuations can reduce sales planning complexity by implementing mass customization. This will improve sales planning reliability. However, the make-to-order concept in mass customization assumes that customers do not immediately receive their configured products. Nevertheless, customers will accept a certain delay between order and delivery. This is essentially due to the fact that customers rather value the additional benefit provided by the customized product.

In addition to the reduction of complexity at the end product level, mass customization involves a decreasing complexity at the work-in-process inventory. This is essentially due to the implementation of flexible manufacturing systems. It is true that these modern systems induce high scheduling problems, but their basic advantage consists in their ability to considerably reduce setup times and also manufacturing lead times. Furthermore, as aforementioned mass customization encourages standardization of components by increasing the commonality level in- and between product variants. All this will result in decreasing the complexity of the work-in-process inventory. Thereby, not only the inventory volumes, but also the numbers of part and component types in the inventory are decreased.

Cutting the Gordian Knot Between Mass Customization and Complexity

Mass customization appears as a strategy that not only increases complexity in the enterprise system but also with some potential to decrease many complexity aspects. On the one hand, mass customization can yield increasing complexity at the configuration, the planning and scheduling as well as the production program levels. We call these aspects complexity drivers. On the other hand, mass customization strongly contributes to the reduction of complexity of the order taking process, inventory and product. These aspects are called complexity breakers in mass customization (Figure 4).

It is relevant to point out that before moving to mass customization, a manufacturer has to outweigh the effects of the complexity drivers and breakers. Complexity drivers may induce additional hidden costs that arise in the form of overheads. Complexity breakers will contribute to decrease complexity for the long term. However, they can involve some single investment costs when e.g. implementing an online configuration system.

Furthermore, it should not be believed that the complexity drivers cannot be influenced. Some measures can be undertaken in order to reduce the magnitude of their effects. For example in order to be able to reduce configuration complexity, it would be advantageous that the mass customizer decouples the front end and the back end systems of the product configurator (Blecker et al., 2004a). Thus, the possible product variants stored in the back end system of the configurator can be very high but the customer will receive only the variants displayed that correspond to his specific needs. Moreover, in order to decrease planning and scheduling complexities in mass customization manufacturing systems, modern approaches such as multi-agent systems can be implemented. Thereby, resources and manufacturing tasks are assigned dynamically in a decentralized way (e.g. Corsten, 1999; Krothapalli/Deshmukh, 1999; Tseng/Jiao, 2001). However, to efficiently decrease the complexity of the production program variety steering concepts for modules' elimination or introduction are of high relevance (e.g. Blecker et al. 2004b).

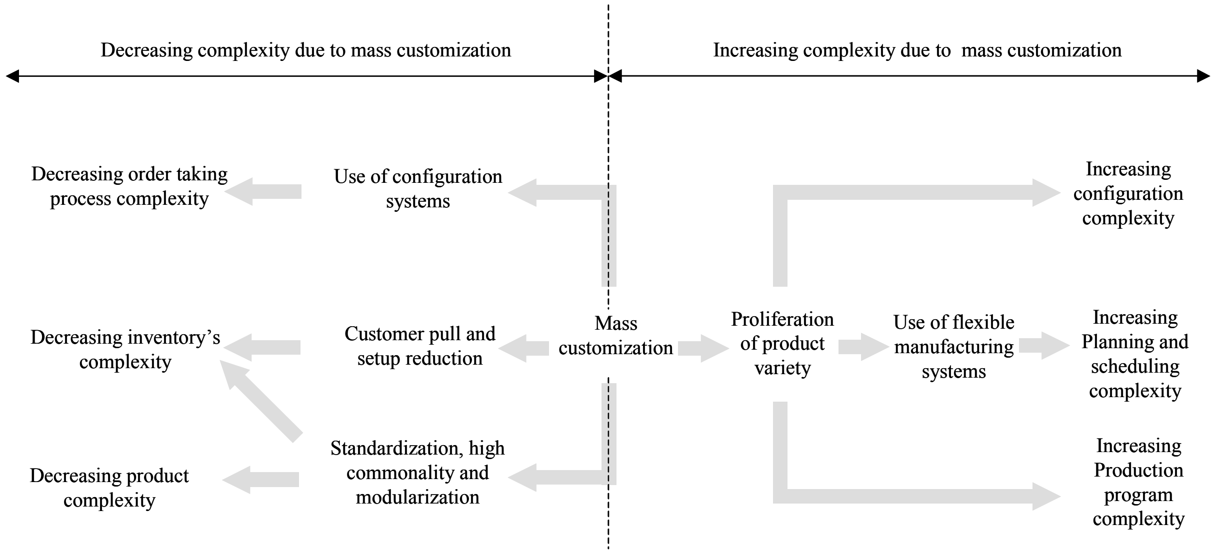

Figure 4: Increasing and decreasing complexity due to mass customization

Conclusion and Research Directions

The basic objective of this paper is to examine the main interdependencies between mass customization and complexity. We have restrained our analysis to a system that consists of three subsystems, namely the product configuration system, manufacturing system and product arrangement system. This restriction is made due to our conviction that the considered system is the most complex one that has to be optimized in a mass customizing enterprise. We have also noted that in order to mitigate high environment complexity characterized by e.g. complex market structures ("markets of one") and rapidly changing customers' requirements, the considered system cannot be a simple one. Therefore, a certain complexity is required and should be accepted when pursuing the mass customization strategy. That is why, an analysis is carried out to examine how mass customization increases complexity. An immediate effect of mass customization is high product variety that triggers high production program complexity, as well as high configuration complexity for customers considered as a subsystem of the enterprise system. Furthermore, the production of a large variety cannot be efficiently realized by mass production systems with high setup times. Thus, mass customization obligatorily assumes the implementation of flexible manufacturing systems on the shop floor. Although these modern systems have a considerable potential to improve manufacturing performance, they increase planning and scheduling complexity.

However, mass customization is a strategy that not only triggers complexity, but also a strategy with some potential to reduce complexity. This perspective of considering mass customization should be emphasized because it contributes towards reaching a competitive advantage. Within the scope of the considered system, mass customization reduces complexity at three main levels which are: order taking process, product and inventory. For example, the competitive success of Dell as a computer manufacturer is basically assigned to the decreasing complexity aspects (complexity breakers) provided by mass customization, namely standardization, low inventory, and direct order taking process from customers. As a result, mass customization does not seem to be an oxymoron with no perspective for success. In some industrial fields, it is even the unique way to outpace competitors. Furthermore, it is also pointed out that the complexity increasing aspects (complexity drivers) can be better kept under control by implementing innovative solutions such as multi-agent systems in manufacturing or information systems decoupling the back end and the front end systems of the configurator.

Further research will be undertaken to develop measurements to objectively assess the complexity of the considered system in mass customization. With such measurements, it would be possible to evaluate the complexity of the manufacturing system as the decoupling point moves towards the beginning or the end of the value chain. It is also very important to be able to evaluate how the complexity of the manufacturing system or the product arrangement system changes when new product variants are introduced to or removed from the production program. It will also be interesting to develop methods to evaluate the complexity of the configuration process. Thus, research on complexity in mass customization is indispensable and should have a main objective that is to ensure a more successful implementation of the strategy in the practice.

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