Chapter 3
Mass Customization Challenges of Engineer-to-Order Manufacturing

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3.1 Introduction

Mass customization (MC) is the capability to offer individually tailored products on a large scale [1]. Moreover, it is about developing, producing, marketing, and delivering affordable goods and services with enough variety and customization possibilities that nearly everyone finds exactly what they want [2]. The concept offers new opportunities to companies combining a mass production tradition with a high level of customization, maintaining high efficiency while offering highly customized products. MC is considered a dominant form of production in business-to-business and business-to-consumer, high-end, and major consumer markets [3]. MC has got great attention in several industries during the last two decades, but its adoption in practice has been slow seen in terms of the increasing interest and major potential [4–6].

Engineer-to-order (ETO) manufacturing environments are typically characterized by high levels of product and process variation, high product complexity and deep product structures, and low production volumes. Each new order involves product design and development based upon customer specifications, and products are typically highly customized. Moreover, design, delivery speed, and flexibility are typical order winners, and the customer order decoupling point (CODP) is typically positioned at the very start of production [7].

MC literature has traditionally focused on the transition of mass producers, defining strategies to increase customization without any loss of efficiency, while there are few MC studies taking the perspective of custom producers such as ETO

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J. Bellemare et al. (eds.), *Managing Complexity*, Springer Proceedings in Business and Economics, DOI 10.1007/978-3-319-29058-4_3

companies that seek to increase efficiency while maintaining a high customization level [8]. MC and ETO are two different production strategies, but these can be combined into a hybrid MC-ETO strategy [9] or standardized customization strategy [8]. The motivation of ETO companies to move toward MC includes benefits such as reduced delivery times, more precise cost calculations, and reduced specification costs, by increasing standardization of customized products, i.e., limiting product variety [8].

However, compared to mass producers, the MC movement of ETO companies seems more complex [8] as ETO companies meet major challenges when moving toward further standardization, i.e., seeking efficiency in customization of products. ETO manufacturing does not necessarily involve high volumes such as in mass, but often imply low volume production. Current knowledge on the adoption of MC principles is developed with primary focus on mass producers and provides only limited guidance on ETO settings. The problem is that since most knowledge on MC is typically developed for mass producers, its relevance in ETO settings may be questioned. Current studies on MC in ETO focus on product design and configurator issues, and there is a research gap related to major manufacturing challenges.

In this paper, general MC principles are tested in a case company to identify major implementation challenges. The aim is to provide further empirical insights to issues in the intersection between MC and ETO manufacturing that are critical for the development of MC principles that are better suited for ETO manufacturing.

3.2 Methodology

This study is based upon a literature review and a case study of an ETO company. The purpose of the literature was to investigate major challenges of MC in ETO settings. Literature searches in academic databases and reviews of identified articles were carried out in several iterations.

A framework of critical areas for MC manufacturing [10] was chosen for structuring and analyzing the empirical data. This framework was chosen because it addresses several relevant MC areas in manufacturing and takes both mass production and handcraft production into consideration.

An empirical case study approach was chosen since there was a need to develop further detailed insights to issues of implementing MC principles in ETO. A single case was necessary to ensure enough detail and in-depth insights to major issues of a typical ETO situation. Case company selection criteria included that their operations were characterized as ETO, and they had long tradition of efficiency improvement work in production. They also had put a lot of effort into this work, and they experienced major challenges attempting to increase efficiency in operations while maintaining high product customization and experienced customer value.

The company is characterized as ETO. The products are complex and heavy and are produced in low volume and in high variety. Operations include both parts fabrication such as cutting, welding, grinding, and machining and assembly processes.

There is high flexibility in the replenishment of parts since these can be fabricated in-house and purchased from suppliers.

Case company data was collected in several iterations over a 3-year period. Interviews and discussions with key personnel including plant manager and logistics manager, planning managers, and planners were carried out combined with plant visits. Most of the data was collected in all-day workshops with case company representatives. Both qualitative and quantitative data were collected; data extracts from the ERP system were mainly used to verify data collected from interviews and discussions. Data was used to describe key issues of the case company related to the general MC implementation principles.

3.3 Literature Review

3.3.1 MC Challenges in ETO Manufacturing

While there is a significant amount of MC research in view of mass production, MC has got limited attention in research of manufacturing settings with high customization [9]. The review identified few studies only that deal with issues related to the MC transition of ETO companies. This chapter briefly presents major challenges identified in the literature review.

A general feature of the MC transition is that it typically implies an increased standardization of engineering work [11]. Major issues are therefore related to the design stages including new product development and order-specific engineering phases [9]. The decision to offer less product variety may compromise the entire business foundation of an ETO company [12]. A common challenge is to find the right balance between flexibility and standardization, i.e., to ensure an appropriate level of flexibility to meet customer demands relative to a rational level of commonality between product designs [8].

Definition of a predefined solution space is a key MC capability [13]. However, defining boundaries of a stable product solution space may turn out to be a highly complex task in ETO companies [9]. There is a risk that the solution space is not adequately large to satisfy all customers' requirements [8]. Since ETO products are often based upon a knowledge-based design, they are difficult to standardize to a degree that allows configuration [8, 9]. Concerning procurement, achieving a reciprocal understanding of needs and interdependencies in the supply chain related to the definition of the solution space is seen as a challenge [9]. Another related challenge is to organize and structure product lines into families, platforms, and modular structures and make knowledge more explicit [9].

Simplification of product designs offered may have unfortunate consequences since it may lead to loss of innovative capabilities, greater risk of product imitations, and organizational resistance to simplifying the engineering work [8].

The rigidity of traditional ICT systems is a major challenge for configuring customized products and manufacturing processes [9]. To ensure flexible manufacturing operations, the support of increased information richness of products and processes is further necessary [9].

Furthermore, issues are related to the standardization of knowledge of repetitive design tasks for automation requiring high technical and social competence of engineering team leaders in the development of customer specifications [9]. The required amount of know-how and skills is also challenging especially in the design and use of product configurators [9].

A tight integration between NPD, sales, and engineering support is also necessary to ensure efficient matching of customer needs with defined product variety [9]. With regard to the supply chain, issues are related to managing relationships with more suppliers, spending more time on sourcing market research, and investing in SCM systems integration that are necessary to ensure efficient sourcing and shipping of small quantities of highly differentiated products [9].

3.3.2 MC Manufacturing Principles

A set of implementation guidelines was selected as the starting point for the development of an adjusted MC manufacturing strategy approach for ETO companies. The guidelines are structured into eight main decision areas including market interaction, product, ICT, manufacturing technology, processes, manufacturing planning and control, supply chain integration, and work organization [10].

Some guidelines are only valid for mass producers or handcraft producers that aim to implement the mass customization strategy. It is assumed that ETO production resembles most to the situation of handcraft producers, and thereby, these guidelines are prioritized over the guidelines for mass producers. The guidelines are summarized in Table 3.1 below. Guidelines specifically valid for mass producers are marked with (a) and handcraft producers with (b).

In the following chapter, these principles are tested in a case company to reveal major concerns of implementation in an ETO setting.

3.4 Test of General MC Principles in an ETO Case Company

3.4.1 Market Interaction

The general guideline suggests that the market interaction strategy should be changed into MTO or ATO. Also, mass producers should position the CODP upstream, while it should be positioned downstream for handcraft producers.

In the case company, production orders are based upon customer orders, and engineering is needed to specify a new customer order, i.e., ETO. Since engineering is a major competitive advantage in this market, the underlying ETO

Table 3.1 MC manufacturing strategy implementation guidelines [10]

Decision area	Guidelines
1. Market interaction	Change the market interaction strategy to MTO or ATO
	(a) Aim to position CODP upstream in the value chain
	(b) Aim to position CODP downstream in the value chain
2. Products	Offer high level of customization on components/modules that represent the highest added value to customers
	Make a product program based on similar design elements for all product families
	(a) Modularize components to enhance the variability for the customers
	(b) Standardize components to reduce the complexity for the manufacturing
3. ICT	Establish online order registration
	Establish a product configurator
	Guide the customer through the order process and visualize the choices
	Strive for seamless integration of all information system (CAD/CAM, product configurator, ERP, order tracking, etc.)
4. Manufacturing technology	Strive for automation in manufacturing, but balance it toward the flexibility obtained by human resources
	Utilize efficient technology in processes upstream of CODP
	Utilize responsive and flexible technology (FMS) in customer-specific processes
5. Processes	Establish a product-oriented material flow
	Design a layout that reduces nonvalue added processes
	Manufacturing processes should perform operations based on digitally transferred information about customer specifications
6. Manufacturing planning and control	Introduce demand-driven replenishment of standard components and modules
	Define and prioritize criteria for sequencing of orders in customer-specific processes
	Aim to introduce push-pull principle in processes upstream of CODP
	Aim to introduce push-pull principle (FIFO) downstream of CODP
7. Supply chain integration	Establish JIT partnership with suppliers of standard components/modules
	Allow key suppliers of customer-specific components online access to the order system
	Establish rapid distribution channels to all the markets areas
8. Work organization	Train operators to be multiskilled
	Educate operators in multiple tasks
	Develop a flexible job rotation and job allocation system

strategy is an essential business foundation. The process of specifying new customer orders typically starts well in advance, between 6 months up to several years. There is thus often a high certainty in the long-term delivery plan. However, it is common that change orders, changed times of delivery, and engineering specification adjustments are defined after the start of production. Forecasts of expected new orders are used to initialize production and purchasing to deal with long lead times and ensure high process efficiency in production.

Spare parts are produced to stock due to the criticality of the delivery time of such parts. For new products, the customer delivery lead time is typically significantly longer than the required production lead time. In practice however, due to late change orders and order specifications, the actual time between that orders is completely specified until delivery is often significantly shorter than the production lead time. This means that the company has decided to start production before the order has been fully specified. Some years ago, the CODP was placed at the very start of operations. However, in order to keep a high level of resource utilization, the company has moved the CODP further downstream. Today, the primary CODP is therefore located at the parts inventory.

Even though there is a unique drawing for each new product, most parts are produced to stock long in advance of start of assembly operations since few parts are customer unique, and parts are often interchangeable. At the same time, there is limited degree of parts commonality as the product variety is high with respect to material and size leading to high inventory levels.

The principle of moving the CODP further downstream for highly standardized products may be further investigated in the case company to systematically achieve additional efficiency gains in production including lower inventory costs and WIP levels. In order to define CODP location that permits further differentiated control of product flows, it is critical to more systematically distinguish between products based upon level of standardization or customization.

3.4.2 Products

It is suggested that high level of customization should be offered on components or modules that represent the highest added value to customers. It is further proposed to form a product program based on similar design elements for all product families. Mass producers are recommended to modularize components to enhance the variability for the customers, while handcraft producers should standardize components to reduce the complexity for the manufacturing.

In the case company, about 80 % of a product's parts are delivered as standard parts. Some components are customized more often than others. However, the company has not defined any specific limitations regarding what components that may or may not be customized. The products may therefore in theory be entirely customized to meet specific needs of each unique customer. A new drawing is created for each new product.

The company has an overall product program consisting of four main product families that include products with similar design elements. Since each product family in turn consists of a wide range of variants and models, the product variability is high.

Even though only a small part of the total number of components of a final product are actually customized, the high number and variety of components still implies high complexity in the company's production processes. Further standardization of components may of course help the company to reduce complexity. However, there is also a risk that increased standardization will have consequences for the company's ability to deliver customer-specific products and thereby its competitive position.

3.4.3 ICT

ICT-related principles include the establishment of online order registration and a product configurator. It is also recommended that customers are guided through the order process and choices are visualized. Moreover, all information systems should be seamlessly integrated.

The case company does not have a product configurator but utilizes CAD/CAM software to visually support the interaction with customers during the sales and order specification process. Drawings and engineering specifications are available via the ERP system. These are also used for generating work orders for parts fabrication. Engineering changes are frequent throughout the production process, and it is critical that changes are taken into consideration as early as possible to avoid rework or build up inventory. Increased ICT integration with regard to engineering change information in the company could improve current practices by rapid communication of changes from engineering to production so that these can be taken into consideration in the production process without delay.

3.4.4 Manufacturing Technology

It is suggested to strive for automation in manufacturing, but balance it toward the flexibility obtained by human resources. This implies the use of efficient technology in processes upstream of CODP and of more responsive and flexible technology (FMS) in customer-specific processes.

The case company has a long tradition of automation in flexible machine resources used for parts fabrication and has several ongoing initiatives related to welding and grinding process automation. Highly efficient and at the same time flexible technology is typically applied in upstream production processes with focus on parts fabrication. For example, flexible machine resources are used to produce both customer-specific parts and standard parts. However, there is a major potential to also automate the physical handling of materials and products in the plant as well as consider flexible robot technology in assembly operations.

3.4.5 Processes

With regard to manufacturing processes, companies should establish a product-oriented material flow with a layout that reduces nonvalue added processes. Also, operations should be performed based on digitally transferred information about customer specifications.

The company experiences major challenges with long lead times in production, and there is lack of flow and product focus in the plant. This can be explained by a long tradition of high resource efficiency and strong focus on machine capacity utilization. Value added time may be improved by a new layout. However, most machine equipment in the plant is heavy and large and therefore difficult to move. These resources are also shared as they are used for parts fabrication to all product families. Information about customer specifications are directly transferred to machine operators, and software programs are uploaded to machine resources used for automated fabrication of parts. Flow orientation of processes has high priority in the company to reduce production lead time and increase value added time relative to nonvalue added time. Focus in this work is on the interface between machine resources and assembly operations.

3.4.6 Manufacturing Planning and Control

The recommended design of planning and control processes is to large extent determined by the position of the CODP. Demand-driven (just-in-time) replenishment should be established for standard components and modules. Typically these are produced upstream of the CODP, but also downstream customer-specific processes will contain some standard components that can be replenished. Sequencing rules that takes delivery dates, capacity constraints, and setup times into account should be introduced downstream of the CODP in order to synchronize the production of different components of a customer order and to roughly keep the pace of the bottleneck. The flow upstream of the CODP should be based on supermarkets and pull, while the downstream flow should be based on first-in-first-out (FIFO) lanes.

The company has a traditional forecast-driven replenishment of materials. The supply of components is controlled through material requirement planning (MRP). The MRP calculates planned work orders and purchase orders based on the company's customer order backlog. They are now introducing a standard pull system for the supply of standard inexpensive short lead time items. However, the majority of parts are either customized, capital intensive, or long lead time items that will be ordered based on MRP calculations. Work orders, drawings, and work instructions for machining, welding, subassembly, final assembly, etc., are released to the different departments of the factory. The flow between operations is to some extent controlled by the due dates on work orders, but the flow is not synchronized, and delays due to missing parts are common. Most of the production is customer specific, and the company is now establishing sequencing rules in order establish takt and a synchronized flow from the CODP. Customization, deep product structures, a large product mix, and high variation work content make this synchronization challenging. A push-pull planning model is developed to ensure that all customized and standard parts for a complete product are delivered just-in-time to the assembly operations and that all operations in each value stream are producing to the same takt.

3.4.7 Supply Chain Integration

The supply chain for mass customized products needs to be streamlined and integrated from end-customers to suppliers. The recommended design for effective supply is to replenish key standard components just-in-time based on partnerships with the most important suppliers. Customized components need to be made to a specific customer order, and suppliers of customized components should be allowed online access to the order system in order to build what the customer want. Mass customization requires fast deliveries of products right after they are built, and the establishment of direct distribution channels to customers is recommended.

The company is manufacturing capital-intensive goods. Most products are built for new construction projects and are ordered months ahead. Delivery precision is key performance objective for products to new construction projects. However, they also deliver spare parts for the service market, and fast delivery time is crucial for these deliverables. The product delivery ratio is high in the service market. The current strategy to meet the delivery requirement in the service market is therefore to customize and convert a similar product with more slack in delivery time. All customized components are made in-house. Materials are purchased on forecasts and stored in sufficient quantities to meet any change in demand. Standard components are ordered weeks before delivery date in order to ensure that all components are available in time for final assembly.

3.4.8 Work Organization

To build customized products efficiently and with short delivery time requires a flexible workforce. Delivery times should be kept short even if mix and volumes fluctuate. A recommended strategy to cut lead times is to train operators and engineers to be multiskilled and able to handle a larger share of the order cycle. Labor efficiency should be high even when demand fluctuates, and the need for different types of jobs varies. Operators should be educated in multiple tasks, and it is recommended to develop a flexible job rotation and job allocation system that can adapt to fluctuations.

The case company engineers and manufactures advanced and complex products where some tasks require specialized skills and knowledge. For most products, one engineer has the total responsibility for a customer order and provides a single point of contact for the customer. The need for specialized knowledge hampers a fully developed job rotation system at the shop floor. Operators are organized in teams for each function and can do various tasks within machining, welding, assembly, testing, etc., but the rotation between different disciplines is limited.

3.5 Discussion

The literature review revealed several relevant issues of MC in ETO settings. A set of general MC principles were also tested in an ETO company to identify concerns of the specific company setting. Based on the literature review and the case study, major concerns related to decision areas are shown in Table 3.2.

Literature suggests that most issues are related to design phases and that operations, logistics, and procurement rely upon improvements in upstream engineering and design processes [9]. The interdependent relationship between MC capabilities including solution space, robust processes, and choice navigation [13] however proposes that MC capabilities should be developed coherently. The case study shows that issues in the early engineering and design phases are important, but that they are not isolated to these areas. Rather, concerns seem to be related to multiple and interdependent areas. This means that MC capabilities involving several areas are to be developed in parallel rather than in a sequential mode starting with product design. To ensure coherency between changes of both products and production processes in ETO companies, further considerations are needed with regard to achieving synergies between MC capabilities.

3.6 Conclusions

Research on the adoption of the MC strategy in manufacturing companies is dominated by studies on the transition of industrial mass producers to become mass customizers. Consequently, the knowledge base of the application of MC in companies with high degree of customization and crafting is still limited.

An underlying assumption of this work is that even though ETO companies may benefit from applying MC principles, these principles have different implications for such settings compared to when MC is applied in mass production. A literature review was carried out to identify major challenges in applying MC in ETO settings. This was followed by an in-depth case study of an ETO company with focus on testing a set of general MC principles.

The study revealed that major issues of MC in ETO are interdependent across several decision areas and involve manufacturing as well as engineering and design phases. There is limited knowledge of challenges for manufacturing compared to

Table 3.2 Major MC concerns of ETO companies

Decision area	Guidelines	Major concerns for ETO
1. Market interaction	Change the market interaction strategy to MTO or ATO	Production lead time is often long compared to delivery lead time. Difficulties in moving CODP downstream in high-mix, low volume manufacturing without increasing inventory cost
	(a) Aim to position CODP upstream in the value chain	
	(b) Aim to position CODP downstream in the value chain	
2. Products	Offer high level of customization on components/modules that represent the highest added value to customers	High variation in what features are customized in different orders
	Make a product program based on similar design elements for all product families	Engineered products often have unique structures that are difficult to standardize
	(a) Modularize components to enhance the variability for the customers	
	(b) Standardize components to reduce the complexity for the manufacturing	
3. ICT	Establish online order registration	Orders often include engineering changes that cannot easily be specified or communicated via online order registration and product configuration. Requires standardized components and modularization
	Establish a product configurator	Engineering work is highly manual and requires expert knowledge
	Guide the customer through the order process and visualize the choices	
	Strive for seamless integration of all information system (CAD/CAM, product configurator, ERP, order tracking, etc.)	
4. Manufacturing technology	Strive for automation in manufacturing, but balance it toward the flexibility obtained by human resources	Low volumes and high levels of customization make automation challenging
	Utilize efficient technology in processes upstream of CODP	
	Utilize responsive and flexible technology (FMS) in customer-specific processes	

(continued)

Table 3.2 (continued)

Decision area	Guidelines	Major concerns for ETO
5. Processes	Establish a product-oriented material flow	Job shop layout with high degree of shared resources makes flow orientation in processes and layout difficult
	Design a layout that reduces nonvalue added processes	Machine programming tends to be time-consuming as new CAD drawings are required for each new product Manual control might be more suitable
	Manufacturing processes should perform operations based on digitally transferred information about customer specifications	
6. Manufacturing planning and control	Introduce demand-driven replenishment of standard components and modules	Pure pull-based replenishment is less suitable for manufacturing characterized by low volumes and high customization
	Define and prioritize criteria for sequencing of orders in customer-specific processes	Push-pull principles need to be combined to ensure lean flow
	Aim to introduce pull-principle in processes upstream of CODP	
	Aim to introduce push-principle (FIFO) downstream of CODP	
7. Supply chain integration	Establish JIT partnership with suppliers of standard components/modules	Low volumes of standard components, which makes it difficult to establish JIT partnerships
	Allow key suppliers of customer-specific components online access to the order system	Due to frequent engineering changes and complex flows, there is high uncertainty in shared plans
	Establish rapid distribution channels to all the markets areas	Total delivery time depends upon the level of product complexity and engineering changes
8. Work organization	Train operators to be multiskilled	The need for specialized knowledge hampers a fully developed job rotation system at the shop floor. Rotation between different disciplines is challenging
	Educate operators in multiple tasks	
	Develop a flexible job rotation and job allocation system	

product design and engineering issues. This paper provides more in-depth insights to practical consequences of implementing MC in ETO manufacturing. Several directions for further research are suggested. The general MC implementation framework could be further adjusted to ETO settings. The challenges presented in this work may also be tested in additional cases to add even more details to current issues. The study includes one single case of an ETO company. The concerns addressed here should be investigated in other ETO manufacturing settings with different product and production characteristics in a multiple case study. In order to contribute to further implementation of MC in ETO, there is a need to develop new methods and tools for successful development and deployment of MC-based solutions in ETO companies. This also includes new approaches to MC implementation that consider a closer integration between several areas, i.e., manufacturing, NPD and engineering, and so on.

Acknowledgements This research has been supported by the Research Council of Norway. We are grateful for the contribution from the case company representatives involved in this research. We would also like to thank the reviewers for their valuable feedback on an earlier manuscript version of this paper.

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