CHAPTER 7

Mass customization

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Abstract

This chapter briefly reviews and structures strategies for mass customization from the perspective of manufacturing and production. We review the classifications of mass customization strategies and identify the competencies that are likely to be required for each strategy. We discuss the effects of inventory management and develop a theoretical model that is useful for predicting and comparing the routes organizations may take in implementing mass customization in terms of identifying which strategies are most likely to cause the biggest increases in operational complexity. We conclude with brief discussions of two case studies and the lessons these suggest for adopting mass customization.

1 Introduction

New business models for manufacturing industry are emerging, based on the achievements of the last twenty or so years. The Total Quality movement, Just in Time manufacturing and recent developments, such as lean manufacturing and agile manufacturing, have pushed forward the capabilities of manufacturing organizations to be responsive to customers’ demands. However, customers have not been standing still either, and they are now expecting a wide range of products, with high and reliable standards of quality, and at a cost that is similar to that of the standardized product of a few years ago.
Not only are the expectations of the customer rising, and the capabilities of the manufacturers improving, but we forecast the next big advance to be the integration of the Internet into manufacturing. This has already begun, and the impact of full integration of the Internet throughout the whole value chain has yet to be achieved or appreciated. This will affect scheduling all along the supply chain, as well as ordering and final delivery of goods to customers, plus recycling and end-of-use.

In this chapter, we shall examine the underlying principles behind mass customization in Section 2. In Section 3, we shall develop some of the methodology and tools that are available to help in the analysis of mass customization systems, as well as the assessment of the business case for mass customization. Section 4 will discuss the implementation issues of mass customization and the factors that are likely to have the most effect on an organization’s ability to manage a mass-customizing manufacturing system. Section 4 also presents briefly some findings from case studies of organizations that have used mass customization and some of the lessons that may be learned from those experiences. Section 5 ends the chapter with a summary and conclusions. A list of references is included at the end of the chapter.

2 Principles of mass customization

Mass customization is a range of complex strategies that capture some of the features of craft production and mass production. Mass customization enables the manufacturer to produce and market a product that can be customized according to the customers’ desires and still be offered with a reasonable price tag, not too far away from that for the standardized product. At first, mass customization may be regarded as the antithesis of mass production [1], but in fact it is not - the antithesis would be to go back to the times of craft production. Mass customization is aimed at providing customized products and services for individual customers or niche groups on a mass scale without losing the benefits of mass production.

We define that a mass-customized product should fulfil four characteristics:

- uniqueness,
- short delivery lead-time,
- low-price and
- excellent quality.

Additionally, mass customization should take advantage of 1) the capacity of the machinery, 2) short lead-times and, in some instances, 3) economies of scale.

Today, customers want products that have high quality, are low in price, are individual and can be obtained in a very short lead-time. Mass customization can achieve these, but there are some issues that have to be addressed before succeeding, such as information management, customer feedback, product complexity and lead times [1, 2]. Customer feedback has always been regarded
as a very valuable tool in the process of design and enhancement of a product, but the actual flow of such information is not as direct as may be desirable [3]. For this to work, all the data would need to be available in real time throughout the supply chain, requiring imaginative and effective use of the Internet.

In order for mass customization to be feasible, the market has to meet certain conditions:

- fragmented demand,
- heterogeneous niches,
- low-cost and high quality customized products,
- short product development cycles and
- short product life cycles.

Each micro-niche requires to be satisfied with a certain customized product or product range that will not only have to be of excellent quality, but will also have a low price tag and be ready and available when the customer expects it.

One of the most important issues that has to be overcome is the lead-time from the moment the customer places the order for a customized product to the point it reaches him or her [2]. To satisfy such demands from the customers, the products have to be manufactured according to specifications given at the point of sale, and these have to be fed into the production systems in real time. To be able to satisfy this vast range of niches the product development cycle has to be very short, particularly now that the actual product lifecycle is growing shorter. Customers are not willing to wait very long for a product; they are less willing to wait even more to obtain a customized product for which they may be paying a premium.

Mass customization is a complex business strategy made up of several components. In this chapter, we shall focus on the manufacturing aspects of the mass customization strategies. The three aspects that will be discussed here are:

1. location of customer involvement point,
2. inventory strategy,
3. variety offered to customers.

These three aspects of mass customization will be discussed in the sections below.

2.1 Location of customer involvement point

Several authors have developed classifications of mass customization strategies [e.g. 4, 5]. Some of these classifications have placed more emphasis on the customer’s perceptions of the product, but from the point of view of the manufacturing organization, one of the most significant factors is the location of the customer involvement point [6, 7]. This is the point in the manufacturing system where the customer’s wishes start to affect the design, structure, etc. of
the particular item that is being manufactured to a customer’s individual order. The customer involvement point is sometimes referred to as the decoupling point.

A mass customization manufacturing system may be viewed as the combination of a push line, some inventory and a pull line, as shown in Figure 1. The push line produces standard items according to a schedule that may be optimized according to standard practices of order batching, demand forecasting, etc. The inventory contains a stock of semi-finished products or modules. When a customer’s order arrives, an item is selected from the inventory and customized in response to the customer’s individual requests. The inventory represents the point in the manufacturing process where the continuous flow of the push line is decoupled from the responsive flow of the pull line. This is the point at which the customer’s individual requests are accommodated and included in the finished product.

![Decoupling inventory diagram]

Figure 1: Schematic of the mass customization manufacturing process, consisting of push line, inventory and pull line. Products flow from left to right towards the customer.

The location of the customer involvement point or de-coupling point is the key to the mass customization strategy of an organization. The position of the customer involvement point defines the kind of customization that the organization may offer the customer, as well as having a profound effect on how the organization will cope.

According to the position of the decoupling point, we obtain five broad strategies of mass customization, as listed in Table 1.
### Table 1: Definition of mass customization manufacturing strategies.

<table>
<thead>
<tr>
<th>Mass customization manufacturing strategy</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Post-distribution</td>
<td>Any customization is carried out by the customer after receipt of the product.</td>
</tr>
<tr>
<td>2. Distribution-to-order</td>
<td>Customer collects the product from a value-adding retailer who adds some customization.</td>
</tr>
<tr>
<td>3. Assemble-to-order</td>
<td>Customization is carried out by the manufacturer.</td>
</tr>
<tr>
<td>4. Fabricate-to-order</td>
<td>Customer becomes involved at the fabrication stage, after design.</td>
</tr>
<tr>
<td>5. Engineer-to-order</td>
<td>Customer is involved during the entire process.</td>
</tr>
</tbody>
</table>

Let us consider the effects of the position of the customer involvement point, from the two extremes, close to the customer at the right hand end of the manufacturing process, as seen in Figure 1, or at the left hand end, close to suppliers.

The post-distribution strategy involves placing the customer involvement point close to delivery to the customer, with inventory held as finished goods. In this case, the complete range of “customized” options would have to be held so that the customer could select their desired option from stock. In this case, the mass-customizer is actually a high variety manufacturer.

The engineer-to-order strategy places the customer involvement point at the left hand extreme of the manufacturing pipeline, close to suppliers. In this case, very little or no stock may be held, since items have to be ordered to meet each individual customer’s requirements.

In between, the customer involvement point may be located at suitable positions along the manufacturing pipeline, in response to the way in which value and options are added to the basic modules as the product moves through the manufacturing stages. The push line, to the upstream side of the customer involvement point, produces a range of semi-finished variants, which are then stored in the inventory. When a customer places an order, an item is selected from the inventory such that it may be customized and developed to produce the customer’s desired variant. The customization process takes place in the pull line.

The manufacturer’s ability to manufacture a customized item depends on their ability to fill the order by selecting the appropriate item from stock, getting it quickly onto the production line, and completing the manufacturing process as quickly as possible. The winning manufacturing strategy will therefore deliver, amongst others:

- Rapid identification of required semi-finished item from stock,
• Holding the appropriate number and types of semi-finished items in stock,
• Rapid completion of final stages of manufacturing in the customizing pull line,
• Flexible, high quality manufacturing in batches of one in the pull line,
• Managing the capacity of production to match demand and avoid build-up of queues of waiting customers.

Part of the means of achieving these objectives is through the management of the inventory, requiring the setting of an inventory strategy.

2.2 Inventory strategy

The inventory strategy is strongly affected by the position of the customer involvement point, since this determines the number of different semi-finished variants that are held as semi-finished goods. As with any inventory strategy, the manufacturer must balance the value already added to the semi-finished product, the probability of obsolescence and the holding cost. The quantity of each semi-finished product that is held is determined by the desired level of customer satisfaction (i.e. the probability of being able to adapt an item from stock to meet the customer’s demands), the variability in demand and the actual number of items of each variant that are held.

The additional considerations that apply in mass-customizing strategies are the amount of value that has already been added to the semi-finished product, the “fan-out”, and the time to complete the product from the inventory point.

Within a mass-customizing strategy, with some inventory held along the manufacturing pipeline, it is desirable to have as much as possible of the added-value actually added at or close to the final stages of the manufacturing process. This means that the costs associated with holding the inventory are as low as possible, given other considerations of obsolescence, storage costs, etc. However, in practice, the added-value will be added at stages along the manufacturing process. The important lesson to derive is that where possible it is advantageous to design the product so that the value-adding stages should occur as late as possible in the manufacturing process. This also points out the need to identify those factors of the product that are most effective in adding perceived added-value to the product, i.e. as perceived by the customer.

The next important factor to consider is the “fan-out”. This is similar to the flexibility of the product, or customizability of the product. If there are \( m \) different types of semi-finished variant held in inventory at the decoupling point, and \( n \) possible variants available to the customers, the average fan-out is given by \( \frac{n}{m} \), i.e. the number of different final variants that can be made from the items held at the decoupling point. Note that the individual fan-out of every semi-finished variant may be calculated separately. Ideally, one would want a small value of \( m \) at the decoupling point and a high value of \( n \), leading to a high
fan-out. Hence, the modules from inventory can be flexibly and easily assembled or configured to produce the customer’s desired product.

The third factor mentioned above is the time to complete the product from the customer involvement point to the end of the manufacturing pipeline. Again, the ideal situation is for this to be as short as possible, so as to deliver the customer’s desired product to a timescale similar to that for the mass-produced item.

To bring these ideas together, we see that in addition to the usual requirement of balancing costs, probability of meeting the customer’s request and avoidance of waste and obsolescence, the product’s manufacturing process and the range of variants offered must be designed so as to configure the product as late as possible, as flexibly as possible and as quickly as possible. Deciding where to locate the customer involvement point is a complex task, which requires an analysis and understanding of where the perceived value is added to the product and the costs that would be associated with holding the semi-finished variants or modules at each stage in the manufacturing pipeline.

2.3 Number of variants offered to customers ($n$)

The third important factor in choosing the mass-customizing manufacturing strategy is the number of options that will be offered to the customer. In the automobile industry, some models offer only 36 possible variants, while others provide over 39 trillion different options [8]. This is a huge number of options, and places a tremendous burden upon the whole system. On the one hand, from the customer’s point of view, the number of decisions that must be made to select between so many options becomes almost inconceivably large. And from the manufacturer’s position, the management and optimization of the manufacturing pipeline, according to the mass-customization strategy points outlined in the previous two sub-sections, become impossibly difficult to identify. Clearly, there is a point where the number of variants becomes too large to be justifiable.

The number of variants offered to the customer has already been discussed in the previous two sub-sections, in terms of the fan-out that may be achieved under late customization strategies, and the ability of the manufacturing organization to deliver the customer’s order quickly, to a reasonable cost and with an acceptable probability of being able to satisfy the customer within a timescale similar to that of mass production.

We mention a further factor that is important to the manufacturing organization in its management of a large number of customer variants. This is the complexity of the IT system that is required to manage the order fulfilment process. In total, this system must be able to manage the customers’ orders and monitor the state of the manufacturing system. Work-in-progress only needs to be matched with a customer order number when it is retrieved from the inventory at the customer involvement point. A large number of options is likely to drive the customer involvement point further back down the manufacturing pipeline, because of the difficulty of holding and managing many semi-finished options in the decoupling inventory.
A large number of final options offered to the customer is likely to drive the customer involvement point back towards the raw materials end of the manufacturing pipeline. This will also imply a big investment in Information and Communications Technology (ICT) in order to manage the process, which is likely to be costly. This will add to the costs associated with managing the associated inventory and manufacturing process. Hence, the manufacturing organization that is considering a transition to mass customization should think very carefully before taking on a very large increase in the number of final customer variants that they intend to offer.

2.4 Summary of section

In this section, we have considered some of the factors that are relevant to the organization wishing to take up a mass customization strategy. These include the organization’s ICT strategy, the number of final options that it is believed the customers require, the position of the customer involvement point in the manufacturing pipeline, the costs associated with holding inventory at any point in the manufacturing pipeline, how many items ought to be held in stock in order to achieve the desired level of customer satisfaction, what is the fan-out from each semi-finished variant held in stock to the finished goods and the location of the customer involvement point.

It is clear that mass customization is a very challenging strategy for a manufacturing organization to undertake. Before embarking on such a strategy, an organization will have to make a sound business case and will need to look very hard at the need for this strategy and its ability to achieve it. In the next section, we present an analysis of some of the business competencies that an organization ought to have in order to succeed at the various mass customization strategies set out in sub-section 2.1.

3 Methodology and tools

In this section, we will present an analysis of the competencies that a manufacturing organization is likely to need in order to become a mass customizer. In sub-section 3.2, we will present an analysis of the competencies that are likely to be most significant for each of the mass customization strategies mentioned in Section 2. In sub-section 3.3, we present a theoretical model of a mass-customizing organization, and derive a measure of the complexity with respect to the manufacturing strategies. Sub-section 3.4 will discuss the stock control strategies relevant to a mass-customizing organization.

3.1 Competencies for mass customization

The competencies that an organization possesses are crucial to its success, now and in the future. Organizations do not always understand what their core competencies are, and may need to carry out an audit of their strengths and
weaknesses in order to understand better their own competencies. The list in Table 2 offers some of the competencies that are likely to be crucial to achieving and maintaining a mass customization strategy.

Table 2: Five key competencies for a mass-customizing manufacturer.

<table>
<thead>
<tr>
<th>Mass customization competency</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design and new product development</td>
<td>Satisfy customer interests by efficiently (time and resources/cost) developing a concept into a realizable solution that is both economic and effective.</td>
</tr>
<tr>
<td>Supplier management and supply chain agility</td>
<td>Dynamically pool resources to meet the changing interests of customers efficiently and effectively; with decreasing vertical integration, this is increasingly accomplished through relationships with collaborating organizations.</td>
</tr>
<tr>
<td>Production flexibility and capacity management</td>
<td>The ability to remain economic while responding to/absorbing change and fluctuations in customer demands with regards to the nature, volume and timing of production outputs; included are flexibility of tools, processes, products, routings, volume.</td>
</tr>
<tr>
<td>Variety and inventory management</td>
<td>The ability for an organization to manage variety and meet fluctuating customer demands while holding relatively minimal Raw Materials, Work in Progress and Finished Goods inventories. • Variety – the variation of an operation’s output over time in terms of the range of offerings, the volume, mix, and timing of output over time.</td>
</tr>
<tr>
<td>Communications, logistics and information management</td>
<td>The ability to manage knowledge and (customer) information for competitive advantage; the level of integration of the functions along the value chain as evidenced having an explicit strategy, having hardware and processes that support communication and having this need recognized at the strategic level.</td>
</tr>
</tbody>
</table>

To assess its competencies, an organization needs to be able to compare its level of competence with other organizations in the same or a similar manufacturing sector. In order to do this, it might be necessary to call in the help of an outside consultant or advisor who necessarily has a wider perspective on the performance of other organizations.
Having obtained an assessment of its competencies relative to similar organizations, the competencies of the organization may be plotted on a chart similar to that shown in Figure 2.

![Diagram](image)

**Figure 2:** Spider diagram for assessing the competencies likely to be needed for success in mass customization.

In sub-section 3.2, we show how the assessment of competencies may be used to suggest a mass customization manufacturing strategy.

### 3.2 Analysis of competencies according to MC manufacturing strategy

Sub-section 2.1 presented a summary of five mass customization strategies with respect to the manufacturing pipeline. However, mass customization is a complex strategy that involves the whole order fulfilment process. We present in this section a summary of how each of the MC strategies is likely to map onto the competencies proposed in sub-section 3.1. See Table 3.
Table 3: Levels of competency likely to be required for five mass customization strategies.

<table>
<thead>
<tr>
<th>Competency</th>
<th>Post-Delivery</th>
<th>Distribute-to-Order</th>
<th>Assemble-to-Order</th>
<th>Fabricate-to-Order</th>
<th>Design-to-Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>high</td>
<td>low</td>
<td>medium</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Supply chain agility</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td>Production flexibility</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Inventory management</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>medium</td>
</tr>
<tr>
<td>Logistics and information management</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>high</td>
</tr>
</tbody>
</table>

Each of the five manufacturing mass customization strategies has been proposed as a way of organizing the manufacturing pipeline. However, it is absolutely vital to realize that mass customization is a business strategy that will affect every aspect of an organization. Hence, competence in managing the supply chain and designing the product are vital, in order to be able to design, monitor and control a manufacturing system that will be capable of delivering the goods to customers within acceptable bounds of cost and lead-time.

Table 3 may be used in either of two modes. In a **market-driven** mode, an organization may look primarily at the market, and assess the kind of mass customization strategy that is most likely to satisfy the market to which it wishes to introduce its own brand of mass customization. Using Table 3, the organization may then identify the competencies that are likely to be needed and then carry out a gap analysis comparing its own level of competencies with those required. Where its competency is less than that required, it might then consider what level of investment would be appropriate to achieve the required competency, and whether the market return of adopting mass customization would be worthwhile.

In the **competency-driven** mode, the organization may assess its own level of competency with respect to other organizations in the industrial sector and then identify from Table 3 the mass customization strategy that most closely matches its current competencies. Again, a gap analysis may need to be carried out where the competency does not match that proposed for each strategy.
It may also be the case that more than one MC strategy might provide a reasonable match to the competencies of the organization. In this case, it might be possible to adopt one strategy and, if successful, run another MC strategy alongside. This would provide an opportunity for learning and developing, so that lessons from one MC or market strategy could be exchanged with the other, along the lines of the focused factory [9]. However, adopting a mixed or combination strategy would be a big challenge for a manufacturing organization, and ought not to be taken on lightly. Many organizations find that achieving and maintaining success in one MC strategy alone is enough of a challenge.

3.3 Theoretical model of the complexity of a mass-customizing organization

In this section, we present a theoretical model of the manufacturing pipeline of a mass-customizing organization. From this we will derive expressions for the complexity of a mass-customizing pipeline and show theoretically which parameters of the manufacturing pipeline are likely to have the greatest impact on the organization. Refer to Figure 1 for a simple model of the manufacturing pipeline, based on the discussion of sub-section 2.1. The parameters that are relevant here are listed in Table 4.

Table 4: Parameters defining model of mass-customizing manufacturing pipeline.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>number of variants offered to the customer</td>
</tr>
<tr>
<td>N</td>
<td>total number of stages in the manufacturing pipeline</td>
</tr>
<tr>
<td>m</td>
<td>number of semi-finished variants or modules made in the push part of the pipeline and stored in inventory</td>
</tr>
<tr>
<td>b</td>
<td>size of the batch of each product in the push line</td>
</tr>
<tr>
<td>q</td>
<td>number of stages in the pull part of the pipeline, (N = q + r)</td>
</tr>
<tr>
<td>s</td>
<td>number of storage locations in inventory</td>
</tr>
</tbody>
</table>

We shall compare the manufacturing strategies of sub-section 2.1 with respect to the expected amount of information needed to know the state of the system [10, 11]. We use the Shannon definition of information, so that the expected amount of information is equivalent to the entropy of the system. For a system of \(s\) states, each with probability \(p_i\), the entropy is given by:

\[
H_s = -\sum_{i=1}^{s} p_i \log_2 p_i
\]

The complexity which will be calculated here is the structural complexity of a mass customization manufacturing pipeline. The quantity calculated will be the expected amount of information needed to know the state of the system. This is
important to the organization for two reasons. First, the higher the structural complexity, the more effort that will be required in order to monitor and control the state of the facility. This will translate into, typically, ICT infrastructure and software to assist in monitoring and scheduling the manufacturing system. Furthermore, it is also likely that a system with a high complexity will be harder to control and manage in practice and so is more likely to stray from the state predicted by the schedule. Hence, such a system will have the problem of being harder to predict, and so it will be difficult to give an accurate prediction for the customer of exactly when their desired product will be available. Although a competency in managing complexity can be an order-winning strategy, it requires a high level of infrastructure investment and a high level of competency to become a reliable earning strategy.

In order to calculate the total entropy (often referred to as complexity) of the system, we shall break the system up into the three separate components of the push line, the inventory and the pull line. We shall also assume that the system is in a state of maximum entropy, i.e. that the probabilities of occurrence of all relevant states are equally likely. In this example, we define the states to be the products that the system is capable of making. Any further assumptions will be mentioned in the relevant paragraphs.

The push line. We assume that $m$ different products are made in the push line, and are then stored in the decoupling inventory. We also assume that the products are all made in batches of the same size, $b$, and that they are manufactured in the same sequence. Hence, in order to know the state of the push line at any time, only two facts are needed: which product is currently at the end of the push line, and where the start of the next batch begins. Under conditions of equi-probability of all states, which is equivalent to maximizing the entropy, this may be shown [12] to be given by:

$$H_{\text{push}} = \log_2 b + \log_2 m$$

Inventory. We assume that there are $s$ locations in stock, and that each location may be occupied randomly by any item.

$$H_{\text{stock}} = s + \frac{s}{2} \log_2 m$$

Other inventory strategies are discussed in [12], but we present here the entropic formulae for one strategy only.

The pull line. We assume that each of the final variants is equally likely to be ordered by a customer, and that all products are made in a batch of one. We assume that demand matches supply and we ignore the effects of queues of customers. Therefore, each location in the pull line, after the decoupling
inventory, is occupied by a product. There are $n$ possible final variants and with each variant equally likely, the probability of occurrence of each variant is $1/n$. Since there are $q$ locations in the pull line downstream of the inventory, the entropy of the downstream line is given by:

$$H_{\text{pull}} = q \log n$$

We can see that the total entropy of the entire manufacturing pipeline is given by:

$$H_{\text{MCtot}} = \log b + \log m + s + \frac{s}{2} \log m + q \log n$$

This expression describes a push line, followed by an inventory consisting of $m$ variant types randomly assigned, followed by a pull assembly line consisting of batches of size one.

We may compare the effects of the parameters $b, s, q, m$ and $n$ by obtaining the partial differentials, as shown in Table 5.

**Table 5: Effects of different parameters on the complexity of a manufacturing system under a random assignment inventory strategy.**

<table>
<thead>
<tr>
<th>Partial differential</th>
<th>$\partial H / \partial b$</th>
<th>$\partial H / \partial s$</th>
<th>$\partial H / \partial q$</th>
<th>$\partial H / \partial q$</th>
<th>$\partial H / \partial n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expression</td>
<td>$1/b$</td>
<td>$1 + \frac{s}{2} \log m$</td>
<td>$\log n$</td>
<td>$s/2m$</td>
<td>$q/n$</td>
</tr>
</tbody>
</table>

The parameters that will have the biggest effect will depend on the actual values of $b, s, q, m$ and $n$ that pertain in the manufacturing system under investigation. However, we can see that the differentials that have values greater than 1 are $\partial H / \partial s$, $\partial H / \partial q$ and $\partial H / \partial q$, if $m>4$, $n>m>2$ and $s>2m$. The other differentials are less than 1 when $b>1$ and $q<n$, i.e. the number of stages in the pull line is less than the number of possible variants.

From this, we may see that the most significant factors are $q$, the number of locations in the downstream pull line, and the ratio $s/2m$, since these are the only two differentials that are linear rather than logarithmic. The value of $s/2m$ depends on inventory strategy, which will not be discussed in full here, but we can see that to achieve a minimum level of complexity, the mass-customizing
manufacturer ought to minimize \( q \), i.e. the number of stages downstream of the decoupling inventory, which is consistent with the discussion earlier in this chapter in sub-section 2.1 and elsewhere.

The most significant logarithmic factor is \( n \), the number of variants offered to the customer. The influence of the other factors depends on their numerical values, so would have to be assessed depending on the actual values that prevail for the mass-customizing organization, insofar as the simple model proposed can be applied to the structure of the manufacturing process and the mapping of products onto the manufacturing pipeline.

### 3.4 Managing the inventory - lot size, reorder point model

In this section, we shall look at another aspect of the inventory strategy, rather than the assignment of items to storage locations, i.e. the kind of inventory strategy considered in sub-section 3.3 and [12]. We present here the Lot Size, Reorder Point Model which attempts to integrate deterministic and probabilistic models of stock managing. The system relies on being monitored continuously, against the more realistic assumption of monitoring the system periodically [13, 14]. Additionally, the model takes into consideration the effects of lost sales or stock outs.

There is, in contrast with some other inventory models, a lead time for replenishment \( L \). This value will be fixed and known. The demand at any given point is considered unpredictable, so the order for replenishment must be initiated in anticipation of the possibility of a stock out. This will happen at the moment the inventory reaches the reorder point level \( r \), which is to be determined and fixed. There is a probability of actually running out of stock before the new order arrives, even if the lead time is known.

The rest of the variables of the model are defined as follows:

- \( P \) Penalty for either a lost sale or a back order sale.
- \( A \) Cost for placing the order.
- \( h \) Holding cost.
- \( d \) Demand rate is given by, which is an expected value of a random variable
- \( \mu \) Average demand

Figure 3 depicts a possible pattern of the inventory behaviour over time. Note that if the inventory level drops below zero, then back orders are being allowed in the system; otherwise lost sales will occur. Both of these patterns can be represented in the form of a penalty.
The inventory cost for a given period of time is

\[ TC = OC + SC + HC \]

where \( OC \) is the ordering cost, \( SC \) the stock out cost and \( HC \) the holding cost. These will be now developed, in order to determine the optimum order quantity from the supplier.

The \( OC \) is defined as the cost of placing the order \( a \) multiplied by the number of cycles in the period being analysed, defined as \( \frac{d}{Q} \), thus

\[ OC = a \frac{d}{Q} \]

The expected stock out cost \( SC \), in either back order or lost sales form is defined as \( P \) multiplied by the expected number of back orders or lost sales per cycle multiplied by the average number of cycles in the period. Stock outs or lost sales are expected to occur only during the lead time period and only if \( D > r \). Let \( X \) be a function of \( r \) representing the expected number of back orders or lost sales per cycle, thus

\[ SC = P \frac{d}{Q} X(r) \]

Finally, there are two different types of holding cost \( HC \), one with back orders allowed and the other with lost sales. The holding cost with back orders allowed is defined as the expected holding cost, \( h \), multiplied by the average inventory on hold per unit time. The expected inventory level just before the order arrives is \( r - \mu \), where \( \mu \) is the average demand (see above), and the
inventory level at the start of the cycle is $Q + r - \mu$. Thus the average inventory level is

$$\frac{Q + r - \mu + r - \mu}{2} = \frac{Q}{2} + r - \mu.$$ 

Thus, the holding cost with back orders allowed can be expressed as:

$$HC = h \left( \frac{Q}{2} + r - \mu \right)$$

Should there be lost sales, the expected inventory level will be given by

$$r - \mu + X(r)$$

Thus, the holding cost with lost sales is:

$$HC = h (r - \mu + X(r)).$$

See Figure 4 for a graphical representation of the typical cycle, assuming constant demand and steady replenishment.

![Figure 4: Graphical representation of the inventory cycle with steady demand and replenishment.](image)

The total period cost for the case where back orders are allowed is therefore:

$$TC = \frac{d}{Q} + \frac{Pd}{Q} X(r) + h \left( \frac{Q}{2} + r - \mu \right).$$

In the case with lost sales allowed, the total cost is
To find the smallest expected period cost, the function is differentiated with respect to $Q$. Barring extraordinary circumstances, the minimum will occur for values of $Q$ and $r$ that are nonnegative and finite, and will occur at that point where the partial derivatives with respect to $Q$ and $r$ both vanish [13].

$$
\frac{\partial TC(Q,r)}{\partial Q} = -\frac{ad}{Q^2} - \frac{PdX(r)}{Q^2} + \frac{h}{Z}.
$$

Setting equal to zero and solving for $Q$, the optimum is

$$
Q = \sqrt{\frac{2d(a+PX(r))}{h}}.
$$

where $PX(r)$ is the cost attributable to either lost sales or stock outs.

This method is relevant to the mass customization paradigm, since there is likely to be a high level of random fluctuations in the demand for individual variants. However, these results only apply to a single product, so need to be extended to account for inventory consisting of $m$ different semi-finished variants.

4 Implementation issues

In this section, we review and summarize the findings and recommendations from previous sections that discussed manufacturing strategy, competencies, inventory strategy, complexity, order fulfillment, etc. The steps to analysing a mass customization strategy are set out below in sub-section 4.1. Sub-section 4.2 views the benefits of mass customization from a different perspective – that of the manufacturer, rather than the customer. The factors that we identify therein are important in constructing the business case in support of MC. In sub-section 4.3, we discuss some example applications of mass customization and identify some lessons that may be learned.

4.1 Making the business case for mass customization

In this sub-section, we summarize the steps to developing the business case for adopting mass customization.

Step 1. Establish market need. We have seen that the starting point of an analysis of the business case for the adoption of mass customization is an assessment of the market need for mass-customized products. The market need may be assessed according to fragmented demand, heterogeneous niches, low-cost and high quality customized products, short product development cycles
and short product life cycles. Customers expect products that have high quality, are low in price, are individually tailored to suit their preferences and are available in a short lead-time.

**Step 2. Assess competencies.** Having established the business case for MC, the organization must scrutinize and assess its competencies with respect to the standards usually achieved by other organizations within the same business sector, including large competitors as well as SMEs. The important competencies were set out in Table 2 and may be summarized as:

- Design and new product development,
- Supplier management and supply chain agility,
- Production flexibility and capacity management,
- Variety and inventory management, and
- Communications and information management.

**Step 3. Identify manufacturing strategy most closely approximating current level of competencies.** Using Table 3, the manufacturing organization may find the MC strategy most closely matching their levels of competencies. This strategy needs to be assessed to see if it will deliver the kind of customization that is acceptable to the market. Alternatively, the organization may choose a strategy from Table 3 and analyse the changes in levels of competencies that would be needed to achieve that strategy. Remember, it is possible for more than one MC strategy to co-exist in the same sector, as well as in the same factory. Just because an MC strategy succeeded for one company in a sector does not imply that that strategy will succeed for every organization in that sector. We shall return to this point in sub-section 4.3.

**Step 4. Assess the factors most likely to affect manufacturing complexity.** The organization may proceed to identify and design the manufacturing strategy that will be adopted under the new strategy, calculate the number of stages and time spent in the push and pull lines, and where is the most effective point to place the inventory that represents the customer decoupling point. Table 5 and the organization’s own measurements of the values of $n$, the number of possible variants, $q$, the number of distinct stages in the pull line, $m$, the number of types of semi-finished variant that are made in the pull line and that are stored in inventory, and $s$, the number of items in stock, can determine which factors are most significant in reducing the complexity.

**4.2 Advantages of mass customization to the manufacturers**

As has already been discussed, the main advantage of mass customization is the ability of the manufacturers to satisfy the demand of a fragmented market. As consumers are becoming more and more demanding and individualized, the market cannot be seen as a single entity with stable, relatively homogenous
shares and a few “specialized niches”, rather the market is becoming more and more fragmented into niches, with specialized needs; and these niches then fragmenting into smaller entities known as micro-niches [1, 2].

A second and equally important advantage is the ability to become more responsive to the demand changes of the market and to build up long-term relationships with individual customers. Customer feedback has always been regarded as a very valuable tool in the process of design and enhancement of a product, but the actual flow of information is not as direct as may be desirable [3, 15]. Today, configurators are becoming indispensable for mass-customizing manufacturers closing the information gap between the manufacturer and consumer. A configurator is a software program for front end systems that interprets customer requirements into buildable configurations, creating the assembly and manufacturing specification for the particular product the customer wants. Additionally the software allows:

1) the customers’ preferences to be stored for further analysis and interpretation,
2) order accuracy and
3) full information exchange between the customer and the rest of the operations in the company.

As already mentioned in Section 1, mass customization is a development within the context of agility, leaness and Just in Time manufacturing. Mass customization demands a lean, responsive manufacturing environment, focused on the delivery of goods rapidly and effectively to the customer. The mass-customizing manufacturer will achieve this goal by a thorough analysis and understanding of the processes that lead to successful order fulfilment and the competencies of their organization.

4.3 Application examples

In this sub-section, we shall look briefly at two case studies of mass customization, one a failure and the other a success. We shall try to identify some of the contributing factors that led to these different outcomes.

4.3.1 Pitfalls of mass customization: an example

In a case study, carried out at a bicycle manufacturer in 2001, the company ventured into a mass customization project and developed a team that assembled customized bicycles. The dedicated team assembled the product from start to finish at a separate area of the factory, paying attention to the specific characteristics dictated by the customer. This strategy emulated the success of National Panasonic in Japan, which ran a “focused factory”, combining mass production and customization on the same site [9].

Unfortunately the delivery lead-time of the finished product was too long. The main issue the manufacturer faced was the delivery time of the frame of each
bicycle, this being imported from Asia to Europe. Local manufacturing of the frames was too expensive even for the standardized product, and the lead-time for delivery of the frames from Asia was in the order of months, as it was not considered economical to ship individual frames. Ultimately, the company’s European assembly operations were closed down.

The manufacturer had been capable of delivering a mass produced product with excellent quality; but it lacked two of the four characteristics to have a successful mass-customized product: short delivery lead-time and comparable price. Customers are willing to sacrifice perhaps only one characteristic of the four, but asking customers to wait up to 18 months for a high-priced item was not acceptable to the market. Additionally the manufacturer was not taking full advantage of its mass-production capability; rather the product was being handcrafted alongside the main manufacturing operation by a small team.

One lesson that may be taken from this brief example was that the company copied too closely the mass customization strategy of another manufacturer in the same sector, without examining whether the competencies they and their supporting supply chain exhibited matched the strategy they had chosen. Scrutiny of Table 2 and Table 3 reveals that they were not sufficiently competent in supply chain agility for a mass customization strategy involving Assemble to Order or Fabricate to Order.

4.3.2 Is the product really mass customized?
A global car manufacturer allows users in North America to “customize” the product within a range of different options, but this customization does not occur at any stage in the actual supply chain. Rather, once the product has been chosen, the system sends an electronic notification to a dealer who will offer the customer a completely pre-built car with all the options selected. In effect, this car manufacturer is still pushing all finished product to the very end of the supply chain: the dealer.

Car manufacturers find it difficult to deliver mass-customized cars in short lead-times, and one possible mass customization strategy is to substitute distributed stock (Distribute-to-Order) for Assemble-to-Order. This strategy works while the number of possible variants, \( n \), remains fairly low. If the number of product variants should increase, stock levels would have to rise and service levels in terms of delivery times could drop. Through this MC strategy, the car manufacturer is only linking what has been mass-produced with what is currently being demanded. The system is relying on high levels of finished stock to provide a reasonable, customized service, but is vulnerable to stock depreciation and obsolescence and future proliferation of options.

The lesson here is that a successful mass customization strategy has been adopted that offers short lead-times and a comparable price tag. The strategy depends on competencies of variety and inventory management and communications and information management.
5 Conclusions

Mass customization can fail due to a lack of delivery of one of the four key characteristics specified in the definition of mass customization (Section 2). If a customer is to buy a product from a manufacturer that offers box-standard items and mass-customized ones, the difference between the two should be the actual product and perhaps the price, but the time to deliver the product should be very similar or even shorter than in other manufacturers’ mass-production systems [1]. A customer will start to lose interest in the mass-customized product after about two weeks from the time the order is placed.

The information and manufacturing technologies are readily available to make mass-customization a reality, but the supply chain is still adapting to the new production scheme [15, 16]. Today’s supply chains were not originally designed to operate efficiently to cater for the quick responses and vast variations that mass-customization systems demand. One of the key functions of today’s supply chains is to act as a buffer, particularly at the decoupling point, in order to be able to cope with demand fluctuations without altering an economical production schedule at the manufacturing plant.

Mass customization will become a reality, but supply chains and manufacturing processes will need to be re-designed in order to achieve and maintain the flexibility that will be required. Although the Internet will enable the rapid transmission of customer orders and requests along the whole supply chain, the lead-time until delivery to customer will still be governed by the time required to manufacture and transport physical goods. This will require a new approach to the entire process of order fulfilment, requiring closer co-operation along the entire supply chain, with suppliers’ manufacturing schedules being determined not by their own in-house optimization, but by the schedule supplied to them by the customer. The ultimate impact of mass customization and the Internet on manufacturing will be the appearance of distinct value chains, focused on individual product niches and operating according to one customer-driven schedule. These changes we have yet to see, but the benefits to the customer and the manufacturing organizations will be profound and welcome.

References


