Variety Management in Assemble-to-Order Supply Chains

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June 2006

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Abstract

Assemble-to-order refers to a supply chain strategy in which products are not assembled until customer order arrives. It is based on the so-called form postponement that is to hold components at a generic form and to delay the point of product differentiation. The performance of an assemble-to-order supply chain depends on two main dimensions, which are responsiveness and achievement level of scale economies. Responsiveness refers to the capability of fulfilling customer requirements in a fast-paced manner, whereas the achievement of scale economies reflects the degree of operations efficiency.

Assemble-to-order supply chains induce high product variety, which has adverse effects on performance. We use demand volumes as a proxy for scale economies and lead times as a proxy for responsiveness. A matrix that consists of both dimensions can be defined, in which we distinguish between short/long lead times and low/high demand volumes. This matrix is called performance matrix. On the other hand, the consequence that results from product variety is a high demand variability of end products, which also affects the demand variability of components. An analysis of component demand variability enables one to identify the components with low/high demand variability. These components can further be classified into supplied and in-house made components. Thus, a second matrix (called component matrix) with two dimensions, namely variability (low/high) and supply source (in-house/supplier) can be defined. Due to the supply source dimension in the component matrix, the supply chain perspective is also taken into account. The combination of both matrixes into a single one provides the performance/component matrix for assemble-to-order supply chains.

To use the final matrix, it is necessary to compute lead times, demand volumes and demand variability of the supplied and in-house made components. By plotting the components in the matrix, one can determine the problems induced by variety. In order to improve the performance of the assemble-to-order supply chain, the implementation of variety management strategies is necessary. The identified strategies are: commonality, component families, modularity, and platforms. Based on the performance/component matrix, we discuss how these strategies or a combination of them can contribute to derive recommendations that aim to alleviate variety impacts on the assemble-to-order supply chain.

Keywords

Assemble-to-order, Supply Chain Management, Variety Management

Blecker, Th./Friedrich, G./Hvam, L./Edwards, K. (Ed.): Customer Interaction and Customer Integration. Proceedings of the Joint Conference of the International Mass Customization Meeting 2006 (IMCM'06) and the International Conference on Economic, Technical and Organisational Aspects of Product Configuration Systems (PETO'06), Series on Business Informatics and Application Systems Vol. 2, Gito Verlag, Berlin 2006, S. 39 - 55.

1 Introduction

The shift from seller to buyer markets, globalization, and saturation of demand are the main drivers, which considerably increased the power of customers. The times in which customers accepted any color as long as it was black are over. In many business fields, customers have become very demanding to the point that they only ask for individualized products and services. These changes at the customer's level have forced companies to react by developing new operations strategies in order to secure market shares and improve profits. Furthermore, companies have realized that they have to concentrate on their strengths and core competencies while closely working with their partners if they want to effectively and efficiently respond to ever changing customer requirements. Therefore, the alignment of operations with customers' requirements is not the responsibility of a particular firm but the task of the entire supply chain. Nowadays, it is widely accepted that competition takes place between supply chains rather than between individual companies.

Looking at the technical literature, we can note that supply chains can basically be classified into three main types according to the degree of interaction with the market. One can distinguish between make-to-stock, assemble-to-order, and make-to-order supply chains. Whereas make-to-stock supply chains work on the basis of an anticipatory model, in which end products are manufactured according to forecasts, the make-to-order system involves the highest degree of interaction with the market because all manufacturing stages are not initiated until a customer order arrives. The assemble-to-order supply chain is situated between these two extremes and represents a hybrid model for which parts and subassemblies are made to forecasts while the assembly of end products is delayed until customer orders have been received (e.g. Wemmerlov 1984).

Because of the diversity of customer needs, assemble-to-order supply chains induce an excessive product variety. But variety is generally not for free. It can trigger a considerable loss of efficiency due to increasing complexity in operations and manufacturing-related tasks. In order for assemble-to-order supply chains to operate successfully, a tradeoff between diversity and costs should be made. In this context, one has to distinguish between two types of variety that can be external or internal. External variety is the variety that is seen by customers, whereas internal variety is experienced inside manufacturing and logistics (Anderson 1997). In this paper, external variety, which generally represents a marketing strategy decision is supposed to be given. We rather focus on the impacts of internal variety. It is also known that high variety on the final product side need not necessarily imply large variety on the input side. There are usually some possibilities to decrease the internal variety level, while keeping external variety the same. The main purpose of this paper is to develop a framework for the analysis of the effects of internal variety on supply chain performance. The second objective is to use this framework in order to apply variety management strategies more effectively.

2 Assemble-To-Order Supply Chains: A Literature Review

There have been a large number of research articles addressing assemble-to-order supply chains from different perspectives. However, authors use in their writings different terms to refer to this concept. The terms which are frequently used as surrogates for assemble-to-order are: build-to-order and configure-to-order. In the attempt to remove some confusion concerning the definitions of these terms, Song/Zipkin (2001) consider configure-to-order as special case of assemble-to-order. They mention that the main difference between both systems actually lies in the way of eliciting demand but not in operations. In effect, in the configure-to-order system, the components are classified into subsets, from which customers select the required components, while in the assemble-to-order system this may not be the case. Gunasekaran/Ngai (2005) point out that in build-to-order, the components and parts are ready for assembly. They define the build-to-order supply chain as "the value chain that manufactures quality products or services based on the requirements of an individual customer or a group of customers at competitive prices, within a short span of time by leveraging the core competencies of partnering firms or suppliers and information technologies such the Internet and WWW to integrate such a value chain" (Gunasekaran/Ngai 2005, p. 425). The authors emphasize that build-to-order necessarily involves the outsourcing of different parts and services based on the core competencies of partnering firms. From this, it follows that build-to-order can be considered as a special case of assemble-to-order where the companies in the suppliers' network are operating on the basis of their core competencies.

We define an assemble-to-order supply chain as a system consisting of push and a pull parts. In the push part, undifferentiated components and subassemblies are manufactured to forecasts whereas in the pull part, end products are assembled according to customer specifications. This latter part is customer driven and largely determines how long customers wait between order placement and delivery of final products. Thus assemble-to-order supply chains trigger longer delivery times than traditional supply chains, in which products are directly picked out from the shelf. However, customers generally accept this delay because they highly value customized products which naturally require a specific time for assembly and shipment after order placement. It is worth noting that though customers would accept a certain delivery time; they would not agree with any delay. Dell is a good example of successful assemble-to-order supply chains in the computer industry. As the company was founded by 1984, other computer manufacturers were characterized by a high level of vertical integration with massive structures. The idea of Dell was to implement lean structures, while producing on customer demand and bypassing the retail through an innovative use of information technology. Due to a close relationship with suppliers, Dell optimized its inventories of components and operated its assembly system with nearly no work-in-process inventory. The assemble-to-order supply chain model enables Dell to reduce uncertainty while minimizing inventory costs in an industry that is characterized by the volatility of customer demand and rapid progress of technology (Magretta 1998).

In the following, we will deal with assemble-to-order supply chains with respect to three important aspects, which are operations, logistics and information technology.

2.1 Assemble-to-Order Supply Chains and Operations

Assemble-to-order can be seen as a form of mass customization with the objective to provide customers with individualized products at near mass production efficiency. The conflicting goals of large variety and good performance are two main concerns that should be well addressed in order to successfully operate the system. The main principle according to which assemble-to-order supply chains work is postponement. Bucklin (1965) defines three types of postponement, which are: time postponement, place postponement, and form postponement. Time postponement refers to the delay of forward shipment of goods, whereas place postponement aims to maintain goods at central locations in the channel. Form postponement is related to the differentiation of the product. With a more focus on the product, Lee (1998) identifies pull, logistics and form postponements. Pull postponement consists in delaying some production activities until the receipt of customer orders. Logistics postponement is achieved if some of the tasks in the supply chain can be performed downstream closer to customers, e.g. in the distribution centers. Finally, according to Lee, form postponement calls for the redesign of the product structure in such a way that some early steps of the process are standardized, while differentiation occurs at later stages. These three types of postponement as they are defined by Lee (1998) are not incompatible with each other, thus making some combinations possible in practice. Due the modularity of computer architectures, Dell had not to redesign the computer. In effect, over the years, the computer has evolved to a highly modular product with an architecture involving standard interfaces; thereby considerably facilitating the application of an assemble-to-order business model. Therefore, it can be stated that Dell just implemented a pull postponement strategy. In many other industries (e.g. automotive industry), there are also many attempts to redesign the products and/or processes in order to enable form postponement and thus to allow for the implementation of an assemble-to-order system. In fact, form postponement is widely argued to be a strategy that considerably facilitates the realization of assemble-to-order systems.

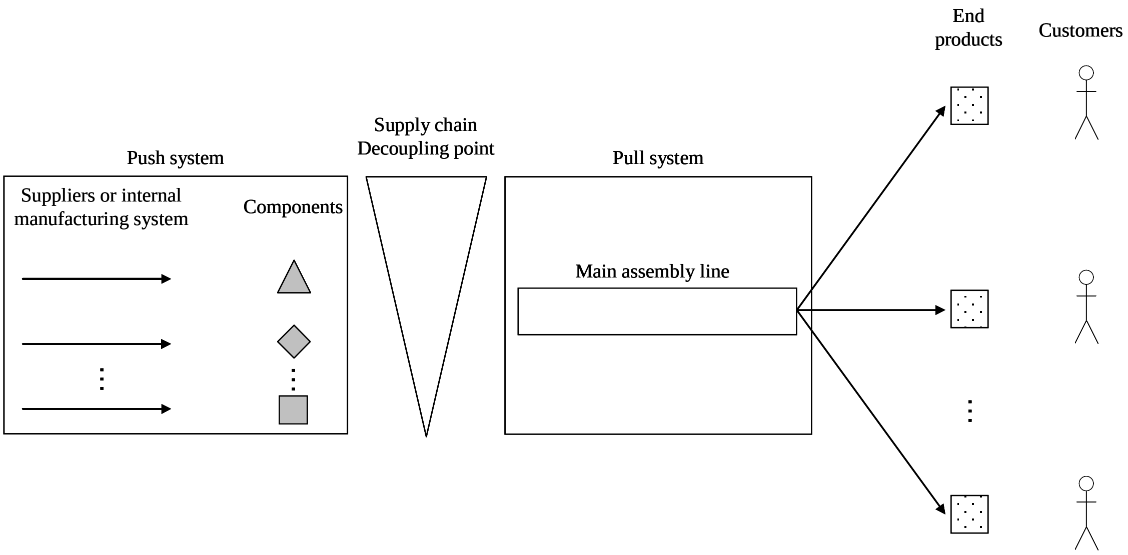

Figure 1: Assemble-to-order supply chain

In order to understand the assemble-to-order system from an operations' perspective, it is important to make the distinction between three particular locations in the supply chain. These are: the supply chain decoupling point, assembly line differentiation point, and assembly line decoupling point. The supply chain decoupling point is situated at the boundary between the push part and the pull part as it is depicted by figure 1. It is the point at which the switch from the build-to-forecast mode to the build-to-order mode takes place. The inventories of supplied and made-in-house components are kept at this point and their corresponding levels are determined by means of stochastic methods. Due to their position in the supply chain, these inventories are sometimes called decoupling inventories. The customization process is initiated in the pull system after the customer order arrives. The necessary components are picked out from stock and combined in the main assembly line into customized products which are shipped to customers.

From the Original Equipment Manufacturer (OEM)'s perspective, there are two positions which are worth to be highlighted: the differentiation point and assembly line decoupling point. We define a differentiation point in the assembly line as a point in which variety increases. For example, the painting station in the automotive industry represents a point of differentiation in which the car bodies assume their unique colors. It should be noted that in the assembly process, there is not only a single but many differentiation points at which the products acquire more identity. In the main assembly line, it is more advantageous to delay downstream the first point of differentiation. Thus, prior to the first differentiation point there are more standardized steps which are common to the entire end product mix. In doing so, the proliferation of variety in the assembly line can be reduced and the assembly time for customized products can be decreased. In this way, the supply chain decoupling point can be even moved to the position of the first differentiation point if the main common subassembly is produced on stock according to demand forecasts.

Whereas the differentiation point is a real point in the process, the assembly line decoupling point is a fictive point which represents an aggregation of the positions of the distinct differentiation points (figure 2). For the same extent of product variety offered, the closer to the customer the decoupling point is, the better would be the performance of the assembly system. For instance, Martin/Ishii (1996, 1997) develop an index called "Differentiation Index" that assigns a value between 0 and 1 to the position of the decoupling point of the assembly process. Index values close to 0 indicate that variety proliferation occurs at the end of the assembly process whereas values tending to 1 indicate that variety increases at early process steps.

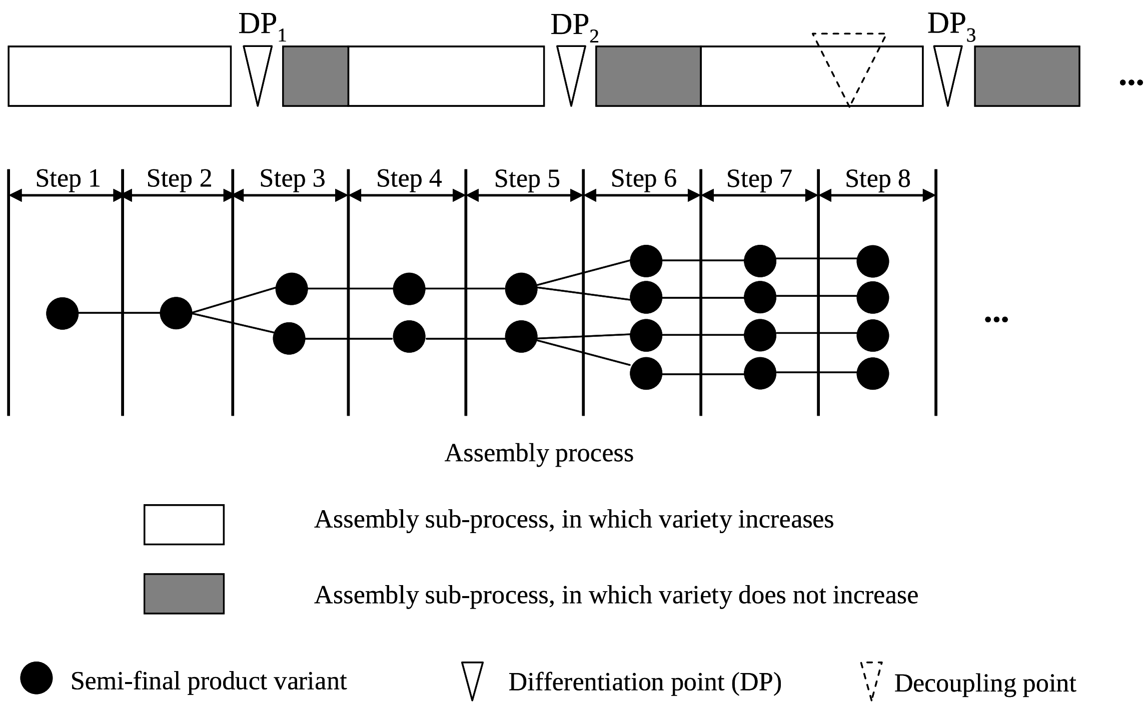

Figure 2: Proliferation of variety in the OEM's assembly process

2.2 Assemble-to-Order Supply Chains and Logistics

Logistics for mass customization and assemble-to-order supply chains is an issue that should be more intensively addressed by researchers. As stated previously, customers accept a certain time for order fulfillment of customized products but they are not ready to accept any delivery time. Equally important is the delivery reliability that is the capability of the supply chain to deliver the product within the promised time span. Chandra/Grabis (2004) recognize that logistics and supply chain management are important key enablers for the success of mass customization and assemble-to-order supply chains since they enable the minimization of product cost, increasing product variety, and shortening time-to-market. In this context, one should make the distinction between upstream and downstream logistics. The upstream logistics take over the transportation, consolidation and warehousing of materials and components that are required for production. On the other hand, downstream logistics ensure the packaging and shipment of end products to customers. Riemer/Totz (2001) point out that the downstream logistics may carry out a part of the customization process since the customer may be provided with the possibility to choose form different logistics options of packaging and transport. Customized packaging (e.g. gift wrapping) or individual delivery times are just few examples which illustrate the involvement of logistics in the process of customization.

However, logistics generally calls for large investments in transportation and warehousing equipment. Especially, for assemble-to-order systems in which the distribution of customized products is achieved on a per item basis, the costs incurred by logistics can be very high, which considerably increases total product costs. Because of this, there is a growing tendency of companies towards outsourcing their logistics operations to third-party logistics (3 PL). Third party logistics are suppliers of logistics services that create value for their commercial clients. They have elaborated transportation networks and can achieve the economies of scale in logistics by consolidating orders from different industrial customers. The services offered go beyond transportation and storage to include value added services, e.g. customized packaging or even final assembly of products (e.g. Lee 2004, van Hoek 2000). Some authors, e.g. Gunasekaran/Ngai (2005) speak about fourth party logistics (4PL) providers which achieve the integration of all companies involved along the supply chain. In fact, there is an endeavor of many logistic companies such as DHL, FedEx, and UPS to provide such services by linking and coordinating the members of the supply chain on the basis of their information and communication systems.

The outsourcing of logistics operations to 3PL and 4PL service providers can also be considered as a response to ever increasing complexity of the logistic system. This complexity is to a great extent triggered by product variety that must be handled in collaboration with suppliers. As variety increases, a more sophisticated coordination among the supply chain is required. Furthermore, there is a need for frequent deliveries in small lots of materials and components in order to reduce uncertainty and costs while improving delivery reliability. However, this requirement necessarily increases transportation costs which can go up drastically. Thus, the configuration problem of supply chains particularly gains in importance when it is to operate an assemble-to-order system. Chandra/Grabis (2004) propose a four steps modeling procedure in order to choose an optimal supply chain configuration. The first step called “Formulation of criteria” deals with the determination of the supplier selection criteria. The second step “Qualification” aims at reducing the set of suppliers, identifying alternative locations for manufacturing facilities and distribution alternatives. At the third step “choice”, different supply chain configurations are evaluated by making use of operations research tools such as mathematical programming. Finally, the last step “Detailed evaluation” aims at examining the retained supply chain configuration by using simulation techniques.

2.3 Assemble-to-order Supply Chains and Information Technology

Due to the nature of assemble-to-order supply chains, before receiving the customer order, it is impossible to determine what end products should be assembled. Therefore, a mechanism for the elicitation of customer requirements and order acquisition is required. In fact, the advances realized in information technology and especially the Internet have enabled companies to operate a direct business to consumer model by eliminating retail. Dell computer and other companies from the automotive industry use product configuration systems in order to make it possible for customers to configure customized products over the Internet. These software systems mainly assist customers in the selection of components and only allow the configuration of consistent product variants that can actually be produced on the main assembly line.

Whereas product configuration systems are implemented at the interface between the OEM and its customers, other types of information systems are necessary in order to enable the coordination of operations with the network of suppliers. For instance, Vendor-Managed Inventory (VMI) enabled by Electronic Data Interchange (EDI) to a great extent facilitates the management of inventories which are located at the supply chain decoupling point. Furthermore, the use of Radio Frequency Identification (RFID) is also promising in assemble-to-order supply chains. With the aid of this technology, suppliers can receive accurate data on a real-time basis that can be used to optimize materials shipments and inventory management. Assemble-to-order systems also call for internal information systems such as product data management systems which should be very sophisticated in order to cope with variety that is induced in these environments. In addition, the integration of ERP (Enterprise Resource Planning) systems among the main members of the supply chain considerably increases the agility and adaptability to unforeseen events. In this way, if unexpected changes arise, the suppliers can immediately react and adjust their activities. Assemble-to-order supply chains would also profit from the advances in software engineering, e.g. service-oriented architectures with the objective to couple information systems of different partners in a loose manner through the use of standardized interfaces and services.

3 Development of a Tool for the Analysis of Internal Variety in Assemble-to-Order Supply Chains

Efstathiou/Zhang (2004) suggest the price-to-consumer and consumer lead-time as two important measures for the evaluation of the performance of a mass customizing system. These key measures can be interpreted as the willing to pay and willing to wait of customers. Chandra/Grabis (2004) also argue that the cost benefit through larger volumes and consistent delivery times are highly significant criteria for mass customization and thus, for assemble-to-order systems.

3.1 The Performance Matrix

We define the performance of an assemble-to-order supply chain as a function that depends on two main aggregate dimensions, which are (1) responsiveness and (2) achievement level of scale economies. Responsiveness refers to the supply chain's capability of fulfilling customer requirements in a fast-paced manner, whereas the achievement of scale economies reflects the degree of operations' efficiency. High internal variety can have negative impacts on both dimensions in that it slows down the supply chain and increases costs, thereby reducing efficiency. We use demand volumes as a proxy for the economies of scales and lead times as a proxy for responsiveness. A matrix consisting of both dimensions can be defined, in which we make the distinction between short/long lead times and low/high demand volumes. This matrix is called performance matrix. It exhibits four main regions as it is depicted by figure 3. Regions 1 and 4 identify the components only satisfying a single performance dimension. The components located in these regions are either supplied within short lead times or their demand volumes are large, thus enabling one to reap the benefits of scale economies. Region 3 represents the worst case situation, in which the components are slow runners and lead times are long. These components are considered bottleneck components. Finally, region 2 identifies the components satisfying both performance measures, namely scale economies and responsiveness.

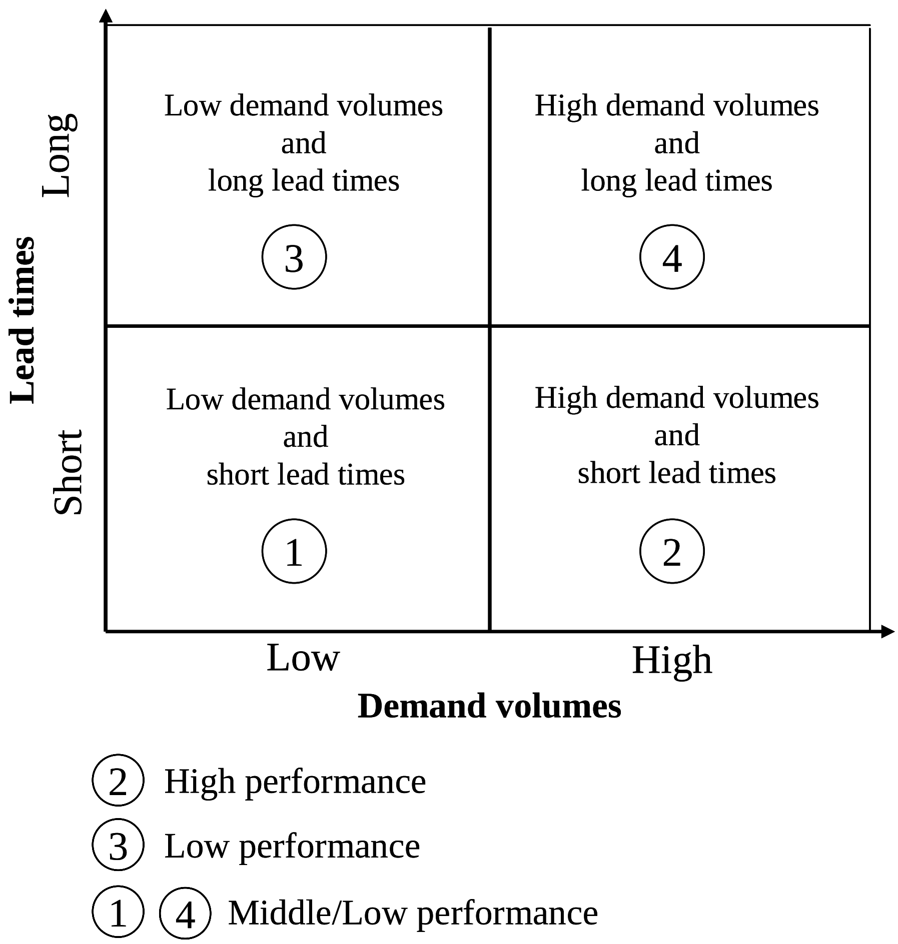

Figure 3: The performance matrix

3.2 The Component Matrix

Variety necessarily increases the degree of demand variability of end products even though aggregate demand may be stable. In fact, variety which refers to the diversity of items and variability which is defined by Hopp/Spearman (1996, p. 248) as "…the quality of nonuniformity of a class of entities" are interrelated concepts. As variety increases, the number of alternatives from which the customer can choose also increases. Thus, the likelihood that customers exhibit a high preference for only a specific set of end products decreases. In this way, demand for end products becomes more variable, which in turn triggers an uneven demand of components. An analysis of the demand variability of components in the product structure enables one to identify those components with low/high demand variability. These components can further be classified into supplied and in-house made components. Thus we can define a second matrix called the component matrix with two dimensions, namely variability (low/high) and supply source (in-house/supplier). Due to the supply source dimension in the component matrix, we take supply chain considerations into account. This matrix identifies four regions as it is depicted by figure 4. Furthermore, it is obvious that the components with low variability are easier to manage than those with higher variability.

For the evaluation of variability, Hopp/Spearman (1996) provide two main measures. The first measure is an absolute measure of variability and can either be the variance denoted by σ^2 or the standard deviation σ, defined as the square root of the variance. The second measure is the coefficient of variation CV that is the quotient of the standard deviation and the mean. It is a relative measure of variability and has more significance than the standard deviation. Let X_i denote the demand random variable of component i with mean m_i and variance σ_i^2, we have $CV_i = \sigma_i / m_i$. By computing the coefficients of variation and making the distinction between made-in-house and supplied components, the component matrix can be established. In the technical literature, there are some attempts to evaluate the effects of variability on the performance of the production system. For instance, Fisher/Ittner (1999) demonstrated empirically that variability in option content has adverse impact on the performance of a company from the automotive industry.

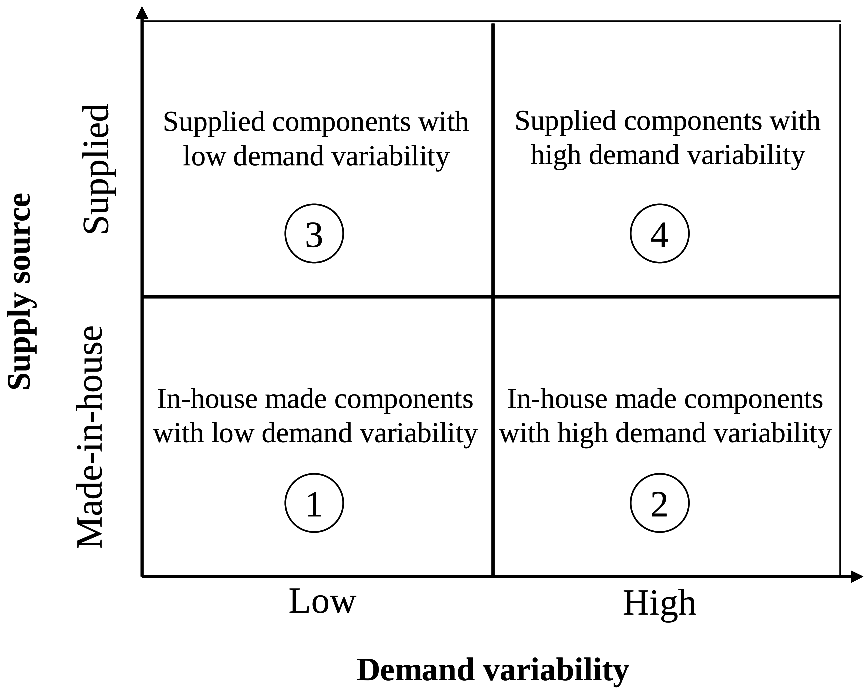

Figure 4: The component matrix

3.3 The Performance/Component Matrix for Assemble-to-Order Supply Chains

The combination of both matrixes into a single one provides the performance/component matrix for assemble-to-order supply chains as it is illustrated by figure 5. The matrix should provide an overview of the components with respect to demand volumes, lead times, demand variability and supply source. Companies operating an assemble-to-order system can plot their components in such a matrix in order to identify some problem areas. It is obvious that the best zone in the matrix corresponds to the region, in which the components have high demand volumes, low lead times and low demand variability. For the outsourced components which satisfy these characteristics, it is advantageous to implement Just in Time (JIT) policies with suppliers for the management of inventory. However, the most problematical components are those with low demand volumes, long delivery times, and high demand variability. These components have a strong adverse effect on the supply chain performance since they slow down operations and considerably decrease efficiency. In order to improve the placement of the components in the matrix, many variety management decisions should be considered. After shortly describing the existing variety management strategies, we will use the performance/component matrix as a framework to examine the effects of these strategies on the improvement of the supply chain performance and on the alleviation of the negative impacts of product variety.

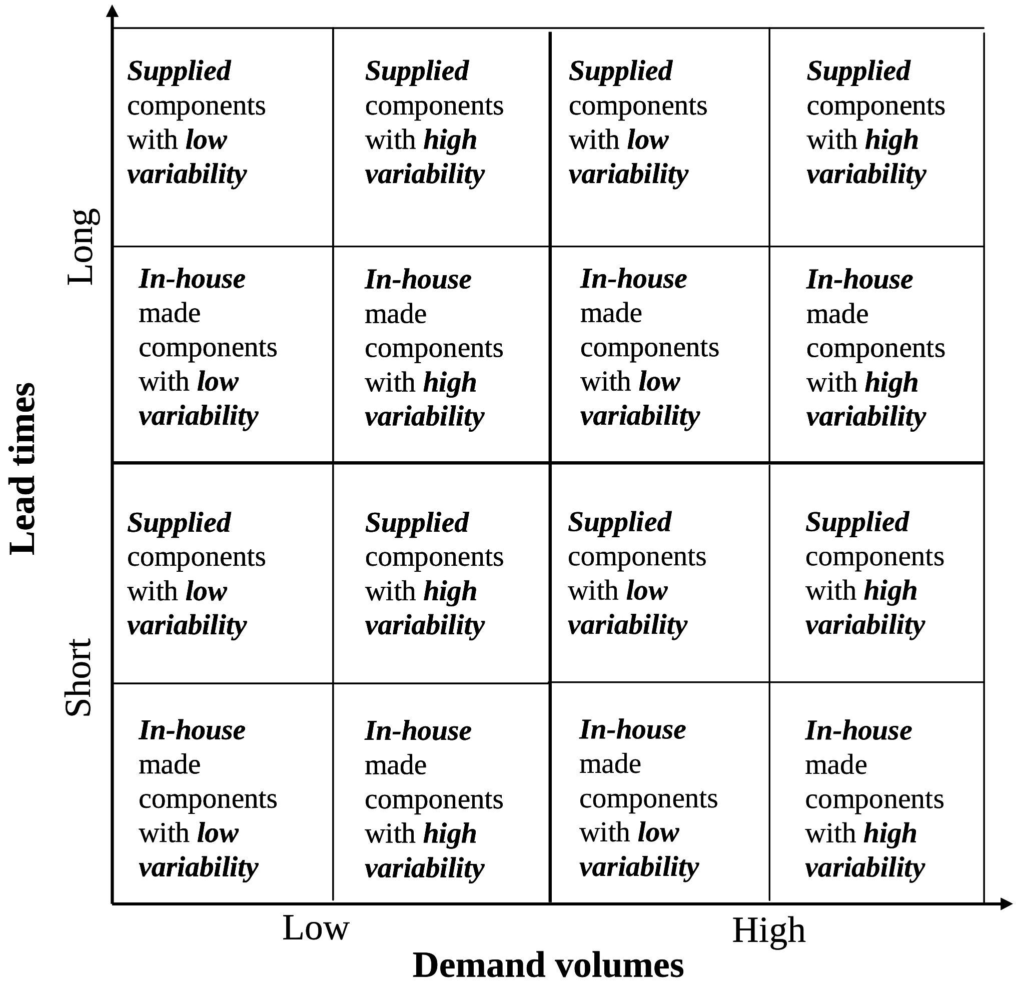

Figure 5: The performance/component matrix for assemble-to-order supply chains

4 Variety Management Strategies

Variety management deals with the reduction, avoidance, and control of variety proliferation. The purpose of variety reduction is to remove useless parts and components rarely utilized in end products. Variety avoidance is not aimed to stop variety development programs but to implement effective instruments in order to make sure that the benefits of variety outweigh its costs. Variety should be accepted if it triggers a profit and rejected if it incurs high costs. However, variety is sometimes unavoidable, especially if individual customer requirements should be fulfilled. This variety that can neither be reduced nor avoided is addressed within the scope of variety control (Wildemann 2003). We can distinguish between four main strategies for variety management, namely: component families, commonality, product modularity and platforms. These strategies enable one to produce variety more efficiently.

4.1 Component families

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

4.2 Commonality

Commonality aims to use few components in as many products as possible so long as it is economical. The attempt to increase commonality between products may result in overdesigned common components. Though such a functional congestion may incur additional direct costs, the benefits of less variety and lower overheads may even be larger. The advantages of component commonality have been widely discussed in the technical literature. One of the most important benefits is risk pooling which leads to more accurate volume forecasts of the common component in stochastic demand environments. Eynan/Fouque (2005) point out that the use of common components reduces variability, which allows for better control and utilization of inventory. In addition, component commonality makes the engineering design process easier and enables the company to benefit from the economies of scale. The use of common components leads to fewer setups on the shop floor, thereby considerably decreasing the manufacturing lead time. Recapitulating, commonality triggers increasing demand volumes due to the frequent use of components in several products, decreases manufacturing lead times because of fewer changeovers, and reduces variability due to the positive effect of risk pooling.

4.3 Product modularity

Product modularity is "…an attribute of the product system that characterizes the ability to mix and match independent and interchangeable product building blocks with standardized interfaces in order to create product variants. The bijective mapping between functional elements and physical building blocks is preferable and refers to an extreme and ideal form of modularity" (Blecker/Abdelkafi 2005). Modularity is an effective means to control complexity. It "…allows the firm to minimize the physical changes required to achieve a functional change" (Ulrich/Eppinger 2000, p. 187). Furthermore, it enables the production of variety while facilitating the achievement of the economies of scale and the economies of scope. From a supply chain perspective, modularity has enabled a new type of component supply called modular sourcing. This approach makes it possible to decrease the extent of vertical integration while reducing the supplier base.

Modularity is an important enabler that makes the implementation of postponement easier. "It separates the composition of end products into parts and/or subassemblies that are common and those that are not" (Lee 1998, p. 88). The design of products around modular architectures triggers a significant reduction of production lead times since long manufacturing lines can be split into parallel production of modules (Ericsson/Erixon 1999). It is worth noting that modularity is to a large extent a matter of interface standardization and that commonality and modularity should be regarded as independent concepts. In effect, a product module may exhibit a high or low level of commonality. This mainly depends on customer preferences. Furthermore, the positive effects of risk pooling need not necessarily be achieved if the product is redesigned according to a modular architecture. Thus contrarily to commonality, product modularity does not enable one to cope with demand volumes variability.

Concerning if modularity increases the demand volumes of components, it is generally not obvious to provide general statements. To illustrate this, let us consider an OEM that outsources two modules 1 and 2 to a supplier. Each module is available in three possible variations. Thus the OEM has to forecast demand and manage inventory of 3+3=6 different components. Suppose now that the OEM defines the module as the subassembly consisting of modules 1 and 2. In other words, the supplier should carry out an additional value adding process that is to assemble modules 1 and 2. The combination possibilities involve 3x3=9 variations of the new module. From this, it follows that the OEM no longer manages the inventory of six different components but of nine components. The demand volume of each module variation as it is experienced by the OEM is smaller in the second case than in the first case. By means of this example, it is obvious that the demand volumes depend on the manner according to which the module architecture defined.

4.4 Platforms

A potential alternative to manage the variety-induced complexity is to implement a platform strategy. A platform can be described as a basic common module that can be used in several variants of a product family. Stotko (2005) summarizes the benefits of platform strategies. He points out that in addition to the reduction of development times and costs, platform strategies support the concentration on core competencies while decoupling the life cycles of the product family variations. More importantly, platforms enable companies to cope with the conflict between customization and efficiency. Therefore, platforms are expected to exhibit large demand volumes and low demand variability. Furthermore, platforms reduce the total number of setups on the shop floor due their high level of commonality among product variants.

5 Impact of Variety Management Strategies on the Performance of Assemble-to-Order Supply Chains

Before discussing the effects of variety management strategies on assemble-to-order supply chains, it is important to note first that the component families mainly influence internal operations. In connection with cellular manufacturing, the strategy is an attempt to reduce the number of setups when producing in-house components. Commonality, product modularity and platforms however, have a wider impact, which goes beyond the company borders to involve suppliers. In effect, platform strategy and commonality may lead to a drastic reduction of the supplier base. On the other hand, product modularity can impact the supply chain in that modules are outsourced to first-tier suppliers within the scope of modular sourcing. For instance, Doran (2003) mentions that whereas a typical car necessitates the coordination of nearly 200 first-tier suppliers the smart car collaboration has been designed using only 25 module suppliers.

Tesrine/Tesrine (2005, p. 179) suggest that for the development of an effective supply chain, "…a company must first integrate its internal processes and then its relationships with suppliers and customers. The first step is to get one's house in order." To effectively manage variety, it is also more suitable that the OEM first initiates in-house reengineering activities such as flattening bills of material, simplifying designs and standardizing components. Then, the alternative to incorporate suppliers in the variety management program must be considered.

The impacts of variety management strategies on the performance/component matrix are outlined by figure 6. The ideal zone in the matrix corresponds to the region, in which demand volumes are high, lead times are short and demand variability is low. However, in some cases it may not be possible to drastically improve the demand volumes of certain components or owing to a strategic decision the OEM may accept to serve a certain customer segment in spite of small component lot sizes (e.g. customers in this segment are willing to pay higher prices). Therefore, we define the second best zone as the region, which consists of the components with short lead times, low demand variability and low volumes.

The first remark that is worth making concerns the frequency of component commonality in the diagram. This high frequency can mainly be ascribed to the capability of commonality to reduce variability and to simultaneously improve the performance dimensions. Furthermore, regardless of the demand volumes and length of lead times, a very important measure that assemble-to-order supply chains should strive for is to reduce variability. In effect, variability is identified as the consequence of product variety with the worst effects on the supply chain such as decreased productivity, increased risk of stock-outs, high levels of safety stocks, etc.

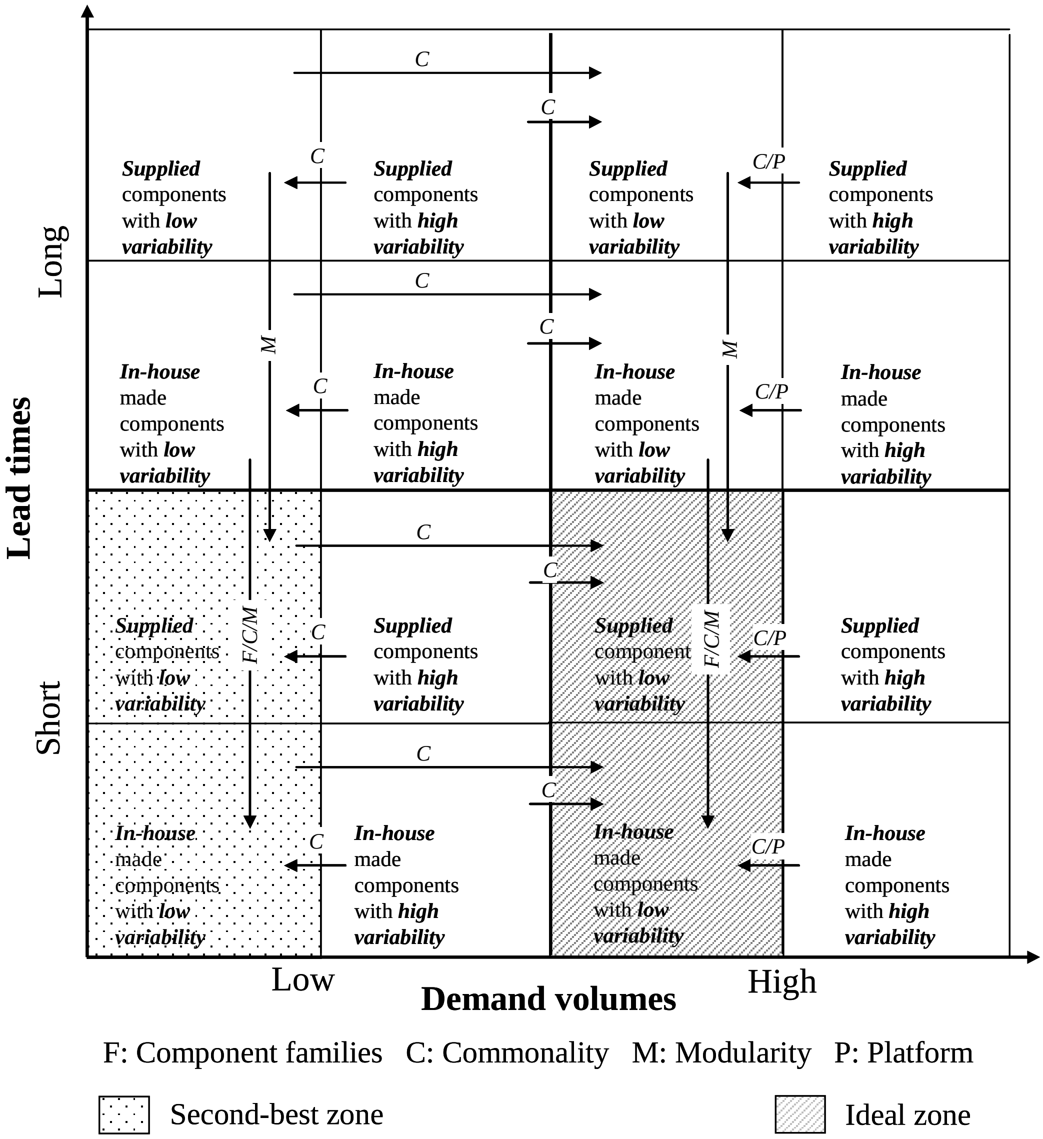

Figure 6: Impacts of variety management strategies on the performance/component matrix

To make the description of the figure easier, we should note the presence of three types of arrows: left-oriented (from the right to the left), right-oriented (from the left to the right), and down-oriented (up to down) arrows. These arrows provide managerial recommendations concerning how to implement variety management strategies effectively in such a manner to improve the performance of the assemble-to-order supply chain in spite of large end product variety. In addition, we should emphasize that it is not necessary to define a diagonal arrow since it can be seen as the sum of a horizontal and a vertical arrow.

The *left-oriented arrows* represent variety management strategies, which are capable of reducing the variability of component demand. Recall that due to risk pooling commonality is the strategy with the greatest potential to alleviate the uncertainty of demand. If demand volumes are low, commonality seems to be the single strategy that enables one to mitigate somewhat the uncertainty of demand. In the event that demand volumes are high, managers can use not only component commonality, but also platform strategies in order to reduce the variability of component demand. The reason why a platform strategy is not suitable for low demand volumes can be derived from the definition of the platform itself. In effect, the platform takes part in all product variants. This lets expect that the components of a platform should exhibit high demand levels. Thus the likelihood to include a component with high demand volume in the platform is much larger than the component with a low demand volume.

The *right-oriented arrows* represent an implementation of the commonality strategy. In this context, we can distinguish between two main transitions in the matrix. Regardless of lead times and supply source, the first transition occurs if commonality is used for increasing the demand volume of components. This transition refers to the case if e.g. two different components with low demand variability are replaced by one common component. Thus, it is expected that variability remains low, but owing to frequent use of the common component; corresponding demand volumes increase. However, the second transition refers to the case when components with high variability and low demand volumes can be moved to the region of the matrix characterized by low variability and high demand volumes.

To explain the *down-oriented arrows*, we should make the distinction between the components outsourced to suppliers and those made in-house. For the supplied components, modularity is the strategy with the greatest potential to reduce lead times. The total lead time of a supplied component consists of the manufacturing cycle time and lead time required for logistics processes such as transportation and shipment. Within the scope of modular sourcing, suppliers do not deliver single components, but entire modules. For this reason, these suppliers are selected on the basis of exigent criteria such as the availability of particular core competencies and the capability of meeting quality and volume requirements. Modular sourcing also calls for a close partnership between the company and module supplier. Therefore, lead times can be negotiated within frame contracts. Furthermore, together with the module supplier, the company can work on developing solutions that aim to shorten lead times. In fact, one important advantage of modular sourcing is that the company no longer has to cope with a large supplier base but only with a few number of module suppliers. This makes every type of cooperative improvement much easier than if single components are outsourced to a large base of suppliers. For the made in-house components, commonality, component family, and modularity can be applied in order to reduce manufacturing lead times. As stated previously, component family and commonality enables one to reduce the number of setups on the shop floor, thereby decreasing manufacturing lead times. On the other hand, the modularity of products enables the company to simultaneously produce the modules and to make the required tests before assembly of the final product.

In order to illustrate how to use variety management strategies, let us consider a made-in house component, for which variability has been ascertained to be high, while demand volumes are low and lead times are long. In fact, this component is situated in the region corresponding to the worst-case situation, which requires urgent actions of improvement. The use of commonality enables one to reduce variability. With an increased commonality, it is expected that the position of the component is either moved to the left if the demand volumes are still relatively low or to the right if demand volumes increase considerably. A further increase of commonality, the use of component family and product modularization enable one to move the component position to the ideal zone or the second-best region. This depends on the extent to which it is possible to increase the demand volume of the corresponding component.

It is important to note that if for certain components the application of the outlined strategies does not lead to a decrease of lead times, other measures can be taken with the objective to improve delivery reliability. For instance, customers who order products consisting of components with longer lead times have to wait longer. This practice is pursued in the book retail, e.g. Amazon. Amazon only holds on stock the books that are frequently asked by customers. For these books delivery times are short. For the books, which are not frequently demanded by customers, a longer delivery time is required.

6 Conclusions

To improve the performance of assemble-to-order supply chains, an integrated variety management approach which spans the OEM and suppliers is required. The attempt of this paper is to provide a tool that makes it possible to analyze the effects of product variety on the supply chain. The tool is represented by the performance/component matrix, which involves four important dimensions: demand volumes, lead times, demand variability, and supply source. The matrix enables managers to implement variety management strategies more effectively. For instance, if a supplied component has long lead times between order and delivery, the tool recommends working on a modular sourcing strategy with the supplier. However, if demand volumes are low, commonality is the most suitable strategy to increase lot sizes and thus, to improve efficiency.

The tool has been already presented to variety management consultants in order to gain some feedback concerning its usability in practice. There is an agreement about the applicability of the tool for assembly-to-order supply chains. Nevertheless, we intend to provide an empirical validation of the tool in the future. An important issue would be the selection of the industrial field, in which the tool will be implemented. For instance, the application of this tool in industries such as the computer industry, in which the use of variety management strategies (e.g. modularity, platforms) has been well established over the time, will not be very interesting. However, a very promising sector we have identified is the house-building industry which experiences a real change towards customized products by implementing the principles of assemble-to-order supply chains. Our future research will also consist in the development of quantitative models that enable a better evaluation of the effects of variety in mass customization and especially assemble-to-order supply chains.

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