ORDER FULFILLMENT IN HIGH VARIETY PRODUCTION ENVIRONMENTS[1]

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Abstract

Providing high levels of product variety and product customization is challenging for many companies. This paper presents a new classification of production and order fulfillment approaches available to manufacturing companies that offer high variety and/or product customization. Six categories of approaches are identified and described. An important emerging approach - open pipeline planning – is highlighted for high variety manufacturing environments. It allows a customer order to be fulfilled from anywhere in the system, enabling greater responsiveness in Build-to-Forecast systems. The links between the open pipeline approach, decoupling concepts and postponement strategies are discussed and the relevance of the approach to the volume automotive sector is highlighted. Results from a simulation study are presented illustrating the potential benefits when products can be reconfigured in an open pipeline system. The application of open pipeline concepts to different manufacturing domains is discussed and the operating characteristics of most relevance are highlighted. In addition to the automotive, sectors such as machinery and instrumentation, computer servers, telecommunications and electronic equipment may benefit from an open pipeline planning approach. When properly designed these systems can significantly enhance order fulfillment performance.

Keywords: order fulfillment, product variety, postponement, open pipeline planning, automotive.

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1. Introduction

Many industrial and business enterprises seek to respond quickly and efficiently to customer demands for specific product variants. When the level of product variety is low and customer demand is largely predictable, then supplying from stock may not present significant risks. However, for many companies, particularly those with high levels of product variety and/or that offer product customization, the costs and risks associated with holding high levels of finished goods stock may be prohibitive.

Product variety is growing in almost all sectors (Cox and Alm, 1998; Bils and Klenow, 2001) and this growth is accelerating. Bils and Klenow (2001) estimated that product variety had increased by 1% per year over a 40 year period. Even more strikingly, their study estimated that most of this growth had occurred in the previous 20 years. The phenomenon is not just associated with consumer products – it is as important in industrial product markets. For instance, Denton et al. (2003) highlight the recent growth in product variety in a traditional industry like steel and the additional pressures that this places on steel producers.

The growth in product variety presents many challenges to manufacturing enterprises. Efficient mass production systems are premised on product standardization and high production volumes. The pre-requisites for mass production are undermined as the variety in the products and product ranges offered by a manufacturing company increases. The operational and transactional costs associated with high levels of product variety are well known e.g. in design, pre-production, forecasting, sourcing and supply chain management, order handling and demand management, set-ups and changeovers and in quality management (e.g. Fisher and Ittner, 1999; Randall & Ulrich, 2001; Ramdas, 2002). The operational difficulties associated with high variety may be exacerbated with global sourcing and globally dispersed production networks (Levy, 1995; Er and MacCarthy, 2006).

When product variety is combined with product customization, i.e. where the customer can specify individual product attributes and features rather than simply choosing from a set of pre-engineered variants, then further operational difficulties arise. Mass Customization approaches have been advocated since the concepts were first introduced by Pine (1993). However, achieving Mass Customization has proved to be challenging in sectors in which it has been attempted (Agrawal et al. 2001; Zipkin, 2001; MacCarthy et al., 2003).

The order fulfillment strategies available to manufacturing companies to respond to increasing levels of product variety and increasing demands for product customization have not received significant attention in the research literature. The standard ‘textbook’ models for production planning and order fulfillment may be of limited value for manufacturing firms in such environments. More flexible forms of response need to be considered. In this paper we consider how producers can fulfill the demand for variety and customization whilst operating efficiently, economically and with speed.

We first consider the range of order fulfillment approaches that are available for manufacturers in responding to increasing levels of variety and customization, some of which are well-established traditional approaches and some of which are emerging in practice. A new classification of these approaches is presented based on how they respond in providing product variety and customization. We then examine one of the more flexible forms of response – open pipeline planning – and its emergence in the automotive sector. Some of the properties of open pipeline systems when combined with reconfiguration in the planning pipeline are illustrated with respect to fulfillment levels and customer lead times. The relevance of the approach to other manufacturing contexts is then discussed, particularly those with high variety and significant upstream pipelines of planned products.

2. Production and order fulfillment strategies for variety and customization

Four standard approaches are frequently noted in production and operations management textbooks to describe how manufacturing companies can respond to demand (e.g. Vollman et al., 1997; Hill, 2004) - Make-to-Stock (MTS), Assemble-to-Order (ATO), Make/Build-to-Order (M/BTO)[3] and Engineer-to-Order (ETO). Essentially these approaches differ with respect to where stock is held in the system and where the production system is decoupled (Olhager, 2003). In MTS it is assumed that production is forecast driven whilst in BTO and ETO it is driven by customer orders. In ATO production is forecast-driven up to the decoupling point and is customer-order driven from the decoupling point. The assumption in MTS is that the product range is pre-engineered (fixed variety) and that the customer selects a required product or mix of products from the range that is offered. In ATO and BTO some degree of choice on product attributes or configuration may be offered to customers. Detailed product design, specification and customization are considered only in ETO.

Typical application domains for some of these approaches are clear. MTS for instance is often associated with fast flowing, high volume and low variety commodity products. However, choices and options for order fulfillment approaches are not always clear-cut.

The nature and complexity of the product, the nature of customer relationships and the amount of competition in the market all influence the approach adopted. The position of a decoupling point will be influenced by technical and design factors related to products and manufacturing processes, as well as the relative costs and risks of stock holding against stockouts. An important additional factor is how long a customer is prepared to wait relative to the cumulative lead times for sourcing, planning and producing products in the volumes that are required. A manufacturer may prefer to adopt an ATO approach for instance but the response times demanded by the customer may require

[3] MTO and BTO are often used interchangeably in the literature, although the latter is more commonly associated with complex products. For simplicity BTO is used in the remainder of the paper.

an MTS approach with potentially greater costs and risks. Balanced against this is that production planning and control may be simpler using MTS.

In this paper we consider the full spectrum of approaches that are available for manufacturing companies in responding to the growth in product variety and the increasing demands for product customization. The spectrum incorporates the approaches noted above as well as newer or emerging approaches. Figure 1 illustrates the spectrum of approaches in diagrammatic form. These have not been presented or described previously in this integrated form. Six categories of approaches are identified.

Category 1 is the standard MTS strategy with fixed variety – the advantages and risks of which are well known. Category 2 comprises the standard BTO strategy. The pure BTO manufacturer typically has a set of product offerings in the form of a catalogue with pre-engineered product variety. Although frequently noted in standard texts, the challenges that arise in adopting a pure BTO approach are not always highlighted. In theory manufacture is not initiated without a firm customer order. Pure BTO requires responsive and efficient production systems and often requires flexible capacity to cope with variability in demand. Holweg and Pils (2004) identify some of the difficulties in moving to BTO in the automotive sector. Where the amount of peripheral variety in a product catalogue is high, producers may, if technically feasible, prefer to adopt an ATO strategy (discussed in Category 4 below) to facilitate more stability in manufacturing operations.

Category 3 covers those companies that allow product attributes to be specified by, or co-designed with the customer, to some degree. These are variations on BTO strategies. The first approach noted is where a limited amount of superficial customization or differentiation is allowed e.g. simply customizing the packaging material or documentation with a product or personalizing the product in some way such as adding a specific customer's name or livery to the product. The next approach offers a more extensive form of customization - functional and dimensional customization. In these cases a customer may be offered a catalogue product but modified in some way to meet their specific application environment. This is often a requirement in machinery and instrumentation sectors. For instance, a company manufacturing large printing presses may customize a machine from its catalogue to fit into a customer's premises (dimensional customization) or to enable a particular feeding or finishing arrangement not offered in the catalogue but sought by the customer (functional customization). A company producing a specific kind of instrumentation may be prepared to modify an existing catalogue product to meet certain voltage requirements not advertised as standard in its catalogue (functional customization).

ETO companies offer substantially more customer involvement in the design and technical specification of products. ETO companies will typically operate within a design envelope in which they specialize and have expertise and technical know how. They will design/co-design products with customers before commencing production. For instance a company specializing in particular kinds of commercial vehicle trailers might be prepared to design, engineer and produce a trailer for a loading application specified by one of its customers but might be unwilling to move into designing trailer variants to attach to specialized construction equipment.

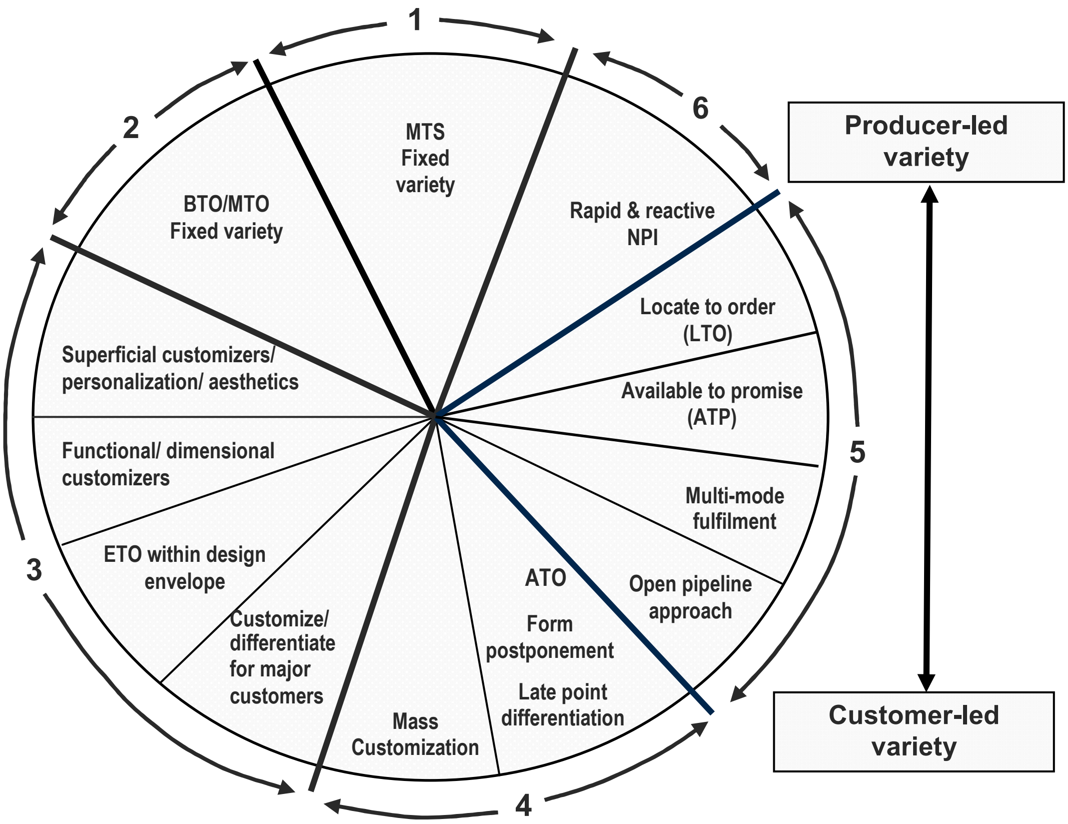

Figure 1. A spectrum of approaches for providing variety and customization

Also noted in category 3 are companies that are prepared to offer customization or product differentiation for specific customers (e.g. major or powerful customers). Commercial vehicle manufacturers for instance usually have very extensive product catalogues with extremely high levels of variety covering all the major attributes of a commercial vehicle. The majority of customers will select a product that is closest to meeting their requirements. However, some major customers – utility companies, public services, equipment hire companies – may request an adaptation of a catalogue vehicle to meet specific needs and the manufacturer will design and engineer a new variant. This could migrate to become a catalogue product at some point in the future. Similar pressures may occur where a powerful customer (e.g. a major wholesaler or retailer) requests a product that meets a specific set of requirements but that is differentiated and made unique for them.

The boundary between BTO companies, functional/dimensional customizers and ETO companies can be fluid – it depends on the level and extent of customer involvement in product design and specification and the degree of adaptation of catalogue products that are countenanced by the manufacturer. Amaro et al., (1999) have discussed detailed differences in companies operating across this category. In the extreme ETO moves into project engineering, environments that are outside the scope of this paper.

Common to the approaches in Categories 2 and 3 is that an order is not commenced without a customer order and a product specification. These approaches are usually associated with manufacturing sectors that have specialist and relatively complex products with a significant degree of design and engineering and where the manufacturer often has a high degree of technical knowledge and competence. There is usually lower production volumes in these categories compared to companies adopting approaches in Categories 4 and 5.

Category 4 covers Mass Customization, postponement and ATO approaches. Environments employing these approaches are characterized by high levels of customer-led variety in products. A range of definitions for Mass Customization have been proposed (Pine 1993; Hart, 1995; Tu et al., 2001; MacCarthy et al., 2003) but the key distinguishing features are that customers must have an opportunity to customize products on a significant number of attributes and the producer must be able to provide this service to a large number of customers without incurring significant additional costs and without requiring the customer to comprise on response times or product quality. Mass Customization does not mean unlimited customization potential for the customer. Clearly it is infeasible to design production systems that could deliver this technically and economically whilst operating on a mass scale. Mass Customization focuses on those attributes on which customers most wish to differentiate (MacCarthy and Brabazon, 2003). This makes it attractive for the customer and operationally feasible and economically viable for the producer.

One way of offering Mass Customization is by adapting the ATO concept so that those product attributes on which customers most wish to customize are achieved after the decoupling point. Products are kept in a standard or common form(s) until late in the production process – so-called ‘form postponement’ (van Hoek, 2001). It is sometimes assumed that form postponement or late point differentiation is the only, or at least the principal means of attaining Mass Customization (Feitzinger and Lee, 1997). However, form postponement may be technically infeasible, very expensive or allow only very limited types of customization. For instance if garments are to be mass customized then dimensional customization is desirable. However, garment shape and size are committed to early in garment production (at the laying up and cutting stage) and most of the garment assembly process follows (making up and sewing). Late point differentiation is therefore technically infeasible for dimensional customization in the garment industry using conventional technologies and production systems.

In practice, the operational modes available for Mass Customization cover a much wider range of alternatives depending on the nature of the customizations that are offered, the balance of customer-led design and pre-engineering, how production resources are used to satisfy customers and when value-adding activities take place (MacCarthy et al., 2003).

Category 5 is an emerging and developing category for fulfilling customers quickly and efficiently with the specific variants they seek. The producer makes or builds to forecast but attempts to satisfy customers by either locating or matching customer requirements with products somewhere in the system or in the planning pipeline. The most basic approach in this category is Locate-to-Order (LTO). This is an important approach in environments where distribution channels and logistics systems are extensive. It is a natural extension of the MTS approach to gain the benefits of inventory pooling by utilizing the entire finished stock across a system to satisfy customers. For instance volume producers in the automotive sector have put in place systems for locating specific vehicle variants in dealerships across a network and in vehicle holding compounds in order to satisfy a greater proportion of customers.

Available-to-Promise (ATP) has been a well established idea in some MRP-driven planning systems where products scheduled for production in the Master Production Schedule are allocated to customers dynamically, allowing more reliability in promising delivery dates (Piebernik, 2005). By utilizing modern ERP tools[4], this idea has developed further for products produced across a network of dispersed production units, sometimes called Global-Available-to-Promise (GATP). Some variations of this approach may allow reconfiguration of the product in the production plan to meet the requirements of a particular customer.

Multi-mode fulfillment mechanisms allow a customer to be fulfilled from multiple points in the system depending on their requirements and current availability e.g. from finished stock, from fixed points in production or by a Build-to-Order product. Denton et al. (2003) describe an application in integrated steel mills where producers are faced with proliferating product variety. To increase responsiveness a customer can be fulfilled from stock, from semi-finished intermediate slab stock made to forecast or by initiating a Make-to-Order product. Swaminathan and Tayur (1998) describe another variation of this approach where orders are satisfied by assembling products either from basic components or from semi-finished intermediate products (called vanilla boxes).

A more general idea is open pipeline planning, which combines elements of LTO, ATP and BTO. Essentially a customer may be fulfilled from anywhere in the system - from finished stock, from pre-planned products in the planning pipeline or in production. If an appropriate product cannot be found then a BTO request is initiated and inserted into the plan. This kind of approach has emerged in the automotive sector to exploit the full potential of the system flexibly to satisfy customer requirements for the vehicle variants. Such open pipeline systems are discussed in more detail in section 3 below. As with ATP, this approach may be further developed by allowing the specification of products in the planning pipeline to be amended or modified to satisfy customer requirements. This type of approach offers a good compromise between building-to-forecast whilst still seeking to meet individual customer requirements for specific variants. Meredith and Akinc (2007) describe an interesting variation of this approach in sectors that manufacture large, heavily engineered products such as specialized machinery, capital equipment or aircraft where fabrication, production and assembly processes are complex and long. Production is initiated to forecast and products in production are modified to meet incoming orders for specific variants as they progress in the production.

In Category 6 the emphasis changes from one of satisfying demand from a fixed range or by customization to a strategy where the producer responds by introducing new product variants to the market place quickly. The dominant expertise and skills required are those necessary for rapid new product introduction (NPI) (Pardy, 2007). The Spanish Inditex company in its Zara fashion clothing business has developed a well-known rapid product design and fulfillment model that can respond quickly to market information on fast changing demand preferences (Ferdows et al, 2004). This is also apparent in some consumer electronics markets with high rates of technological change (high clockspeed) where rapid new product introduction is important (Fine et al. 2002).

It should be noted that, as with most classifications of this type, these are broad categories and specific approaches may be realized operationally in different ways in different production environments. Many producers will combine approaches in planning and managing production across their product ranges depending on demand characteristics.

We now consider the open pipeline approaches in category 5 in more detail and discuss their use in the automotive sector.

3. Dynamic pipeline management in the automotive sector

Open pipeline approaches that facilitate flexible, multi-mode fulfillment to satisfy customer orders are attractive in manufacturing domains with complex products that are faced with high product variety and demands for customization. This kind of approach acknowledges the reality of manufacturing planning and control in such environments (Vollman et al. 1997). The cumulative lead-times for sourcing of components and parts and for the planning of manufacturing and assembly operations may be longer than customers are prepared to wait. In addition there is a need to ensure high levels of utilization of manufacturing and assembly resources. The manufacturer must therefore commit to, and plan for production in future time periods without firm orders i.e. making or building to forecast. This results in a dynamic pipeline of planned products to meet anticipated demand in future time periods.

On the one hand, product variety in the form of extensive product ranges complicates the planning process. On the other hand, in an open pipeline approach, product variety in the planning

[4] See www.sap.com

pipeline can potentially be exploited dynamically in order to match products more precisely with customer specifications.

This type of approach has emerged in the volume automotive sector for a number of reasons (Agrawal et al., 2001; Holweg and Pils, 2004). Firstly, volume automotive production requires extensive planning pipelines to enable efficient supply chain and assembly planning and to cope with the many constraints that arise in practice e.g. a temporary capacity problem such as a limited supply of catalytic converters or regulatory issues such as the CAFE requirements in the US that require certain overall proportions to be met across the mix of vehicles assembled by any particular producer (National Research council, 2003). Secondly these are large scale systems both in terms of planned vehicle builds (measured in weeks) and in the number of vehicles held in vehicle holding and distribution compounds and across dealership networks. In fact the actual vehicle assembly process is relatively short in comparison to the length of the pipeline. Thirdly, the customer base is heterogeneous in terms of its requirements and preferences. Customers differ not just in the precise vehicles they seek but in their willingness to compromise, to trade-off aspects such as price against product features and in their desired waiting time. Customers differ also in their desire to customize vehicles - some are happy to select from the variety that is currently available in physical stock whilst others wish to configure their vehicle in detail.

Thus, flexible forms of fulfillment that can exploit the potential of large scale automotive order fulfillment systems dynamically to meet the requirements of a diverse customer base whilst enabling a continuous flow of production are attractive. In the automotive sector this approach has been called Virtual-Build-to-Order (VBTO) by Agrawal et al. (2001). VBTO combines pipeline searching, matching and allocation of products but also allows BTO when required. Clearly the approach raises many issues with regard to how such systems behave, their critical parameters and how they should be designed and managed. Some of the characteristics of VBTO systems have been analyzed (Brabazon and MacCarthy, 2006). Although these systems may bring many benefits, they require careful design and management to ensure that they deliver enhanced performance over more conventional closed pipeline MTS approaches or pure BTO approaches.

Here we consider an additional aspect in an open pipeline system – that of reconfiguration of products in the planning pipeline.

3.1 Reconfiguration in dynamic open pipeline systems

When it is possible to reconfigure products in the planning pipeline then further opportunities arise for matching customers to products. Thus, a planned product in the pipeline may be altered into the precise specification for a particular customer or may be modified to be close to what a customer has requested or may be left unaltered from its initial planned specification. We illustrate the impact of reconfiguration on fulfillment and on waiting time in an open pipeline system using a simulation model.

We assume we have a pipeline of a particular length which is being fed continuously with a defined range of products at its furthest upstream point. Products move along the pipeline at a constant rate in the sequence in which they are fed into the pipeline. Production and assembly are assumed to occur at the downstream end of the pipeline and are not modeled explicitly. When an unallocated product exits the pipeline it goes into stock. The model also has a customer arrival process. An arriving customer seeks a product from the range on offer. Using an open pipeline system, stock is first examined to find the product variant the customer seeks. If a match is found then the product is allocated to that customer. If a match is not found then the pipeline is searched for a matching product and if found then the pipeline product is allocated to that customer. It proceeds along the pipeline as an allocated product but does not enter stock. If a match is not found in the pipeline then a specific Build-to-Order (BTO) product is fed into the pipeline. This product cannot be allocated to another customer whilst it is in the pipeline and does not enter stock on exiting the pipeline.

Clearly there are many parameters and system variables that can be set in the model described above – e.g. the extent of the product range, the demand characteristics, the feed into the pipeline, the length of the pipeline etc. In order to illustrate the impact of reconfiguration flexibility in an open pipeline system we assume here that the feed into the pipeline is uniformly randomly distributed across the product range and that the demand has the same distribution but is independent of the feed distribution. We assume that customer arrival rate and pipeline feed rate are equal. Essentially this is assuming that production and demand are in balance in terms of volume and mix in the long term. The producer is assumed to be a good forecaster overall but does not react to specific customer demands at any point in time by changing the feed. In large scale automotive order fulfillment systems producers have a reasonably accurate view of overall demand characteristics but such systems are difficult to fine tune to be able to respond reactively in the short term. Hence the model, although simple, is reasonably faithful to some of the overall characteristics of such systems and allows the impact of reconfiguration flexibility in an open pipeline to be illustrated. More technical details of the simulation are available in Brabazon (2005).

We model product variety and reconfiguration flexibility in the following way. The product range is assumed to have N unique product variants, with product #1 being the lowest specified variant and product #N being the highest specified. In the absence of reconfiguration flexibility, the correct variant must exist in stock or in the pipeline for a customer to be fulfilled; otherwise the required variant is fed into the pipeline (a BTO product). When reconfiguration of unallocated pipeline products is allowed i.e. a planned variant can be changed into another variant, there is clearly a greater chance of finding a suitable product in the pipeline. The level of reconfiguration flexibility is modeled here in terms of the fraction of the product range into which any product can be reconfigured.

The impact of reconfiguration on the fulfillment performance is illustrated for a particular set of parameters in Figure 2. Here the variety level N is set at 1024. Figure 2 shows the likelihood of fulfillment for nine levels of reconfiguration flexibility (starting at no reconfiguration flexibility) and for four different pipeline lengths. To explain the reconfiguration level further, if a product can be reconfigured into +/- 10 variants, the flexibility is measured as 20/1024 (~0.02 on the horizontal axis). The length of the pipeline is determined by the number of products in it.

Clearly the longest pipeline offers the greatest number of opportunities to utilize reconfiguration flexibility and relatively low levels of flexibility are needed to have a large effect on the fulfillment level; conversely, with the smallest pipeline length, relatively large levels of flexibility are needed to achieve high levels of fulfillment. More generally, it is evident that the effect of reconfiguration on the level of fulfillment level is affected by the level of variety relative to the length of the pipeline.

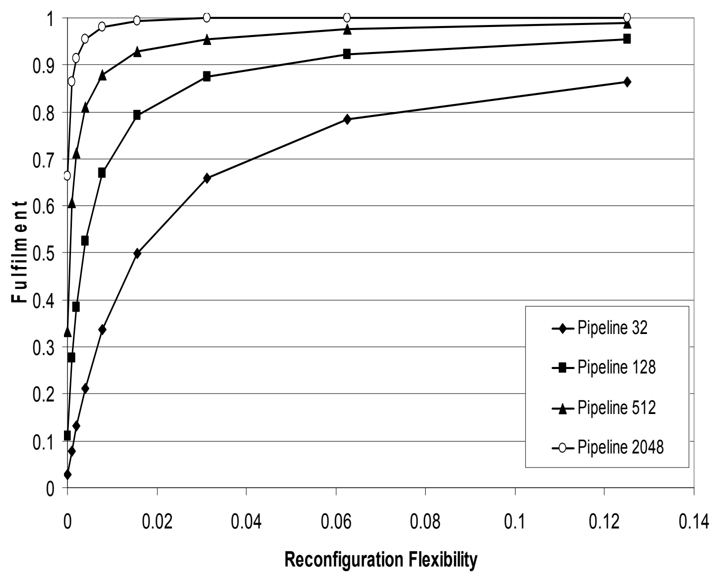

Figure 2. Benefit of reconfiguration flexibility at different pipeline lengths (product range 1024).

Reconfiguration in the planning pipeline can significantly improve fulfillment levels. However, some of the behavior of open pipeline systems with reconfiguration can be difficult to predict. For instance it does not follow that customers are always fulfilled in a shorter time when compared to a conventional system (i.e. an order fulfillment system without pipeline fulfillment where customers are fulfilled either from stock or by a BTO product). As reconfiguration flexibility increases, more customers are fulfilled but they are fulfilled from further upstream in the pipeline, which affects the distribution of customer waiting time. Figure 3 illustrates this effect showing a frequency distribution of the position in the pipeline from where customers are fulfilled as flexibility increases. The overall simulation conditions are as noted above but a shorter pipeline length (128) is used to demonstrate the effect with a specific level of variety (512) at four levels of flexibility (0, 0.016, 0.06, 0.5). As reconfiguration flexibility increases it is seen that more and more customers are fulfilled from further upstream in the pipeline. The magnitude of this effect depends on a number of system parameters, particularly the level of variety and the length of the pipeline.

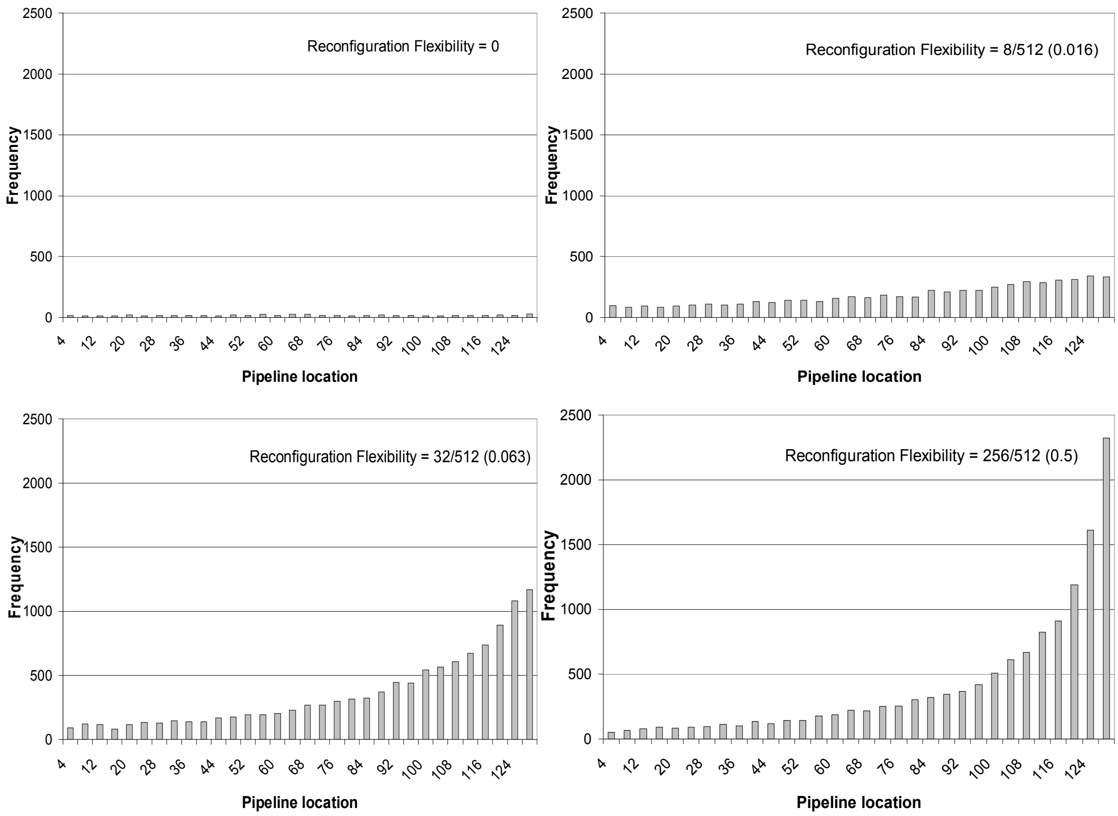

Figure 3. Frequency distribution of the pipeline location from where products are allocated to customers, at four levels of reconfiguration flexibility (pipeline length 128, variety 512).

One of the attractions of open pipeline order fulfillment systems in the automotive sector is the diversity in customer requirements. Reconfiguration in the planning pipeline adds to the flexibility of such systems. By adopting a dynamic open pipeline system with a pipeline reconfiguration strategy there is a potential to satisfy a greater proportion of the heterogeneous customer demand. The degree of impact will depend on the parameters and scale of the system and on how the system is designed and managed. However, as is evident with respect to waiting time, the impact of introducing pipeline reconfiguration flexibility on performance metrics must be considered carefully in designing new order fulfillment systems. Simulation provides an effective tool to investigate the magnitude of such effects.

3.2 Open pipeline systems, decoupling and postponement

The concept of the customer-order decoupling point or order penetration point (Olhager, 2003) may be used to differentiate the standard order fulfillment strategies. This is the point at which the customer order penetrates the production process. Production is based on forecasts up to the decoupling point. The traditional approaches – MTS/ATO/MTO/ETO – may be viewed on a continuum, where the customer-order decoupling point moves further upstream from finished stock holding in MTS to raw material holding in BTO, with intermediate stock holding prior to assembly in ATO. ETO approaches do not have a decoupling point as such – once an order is agreed and it is fully designed and specified, the required materials, components and parts are then sourced or procured. Multi-mode fulfillment systems can be viewed as having multiple decoupling points corresponding to each mode of fulfillment. In the open pipeline system however, customers can be fulfilled from any point in the system and can be viewed as having a moving or floating decoupling point.

A postponement strategy assumes implicitly that later demand information is more reliable and less risky than earlier information on which forecasts may have been based. Hence postponement is advocated to cope with product variety by postponing some parts of the value–adding process until clear demand signals on final product requirements are known with greater certainty. The postponement concept can be interpreted in different ways (Bowersox et al., 2006; van Hoek, 2001; Yang et al. 2004). For instance the LTO fulfillment model discussed in section 2 may be viewed as a type of 'place' postponement where the final location of a product is not decided until a real demand signal is obtained. 'Form' postponement, most commonly referred to in the literature, delays commitment within the manufacturing system on some key physical product attributes until real demand signals are received.

Form postponement strategies imply a single, fixed decoupling point. When postponement is from a fixed decoupling point, customer lead time may be simpler to predict, being a function of the queuing time at the decoupling point and the downstream processing and logistics times. Form postponement relies on re-engineering of product architectures and the manufacturing and order fulfillment processes in a way that ensures that upstream parts of the process can be decoupled for stability whilst downstream parts can be driven directly by current demand requirements. This may not be valuable when there is a significant upstream planning pipeline that requires forecasting and commitments to be made to products attributes prior to production.

The automotive sector is a case in point. Although it is argued that the sector should move to a Build-to-Order strategy (Holweg and Pil, 2004), it has remained strongly wedded to build-to-forecast production. The length of the planning pipeline and the need to satisfy a diverse customer base are important contributory factors. For some customers color may be the principal determinant of choice, for others engine type or engine size and for others a specific combination of features and options may be required. Some customers may have little interest in detailed customization of their vehicle whilst for some it may be the determining factor in a purchase. Satisfying this range of requirements is not feasible with a single fixed decoupling point. Open pipeline systems allow volume automotive producers to achieve more effective order fulfillment by exploiting their extensive product pipelines to satisfy the range of customer requirements. However, as illustrated in 3.1 above, in an open pipeline system with a floating decoupling point, customer lead time is more complex to predict than in a fixed decoupling point system.

4. Applying open pipeline concepts in other sectors

Section 2 described a range of approaches available to manufacturing companies to respond to market needs for product variety and customization. Figure 1 indicates that the approaches that appear in the upper half are dominated by producer-led variety and those in the bottom have a greater degree of customer involvement. A number of factors will affect the choice of strategy (or strategies) that may be adopted e.g. the business and market, how important variety and customization are to remaining competitive, the flexibility in the supply base, product architecture and technology issues, flexibility in manufacturing and assembly operations and the level of complexity in manufacturing planning and control.

It is important to stress that product variety is rarely static. In most cases it evolves as new products and variants are introduced and others discontinued - product ranges develop and mature over time. The rate of change will vary depending on the sector. The optimum production and order fulfillment approach may therefore change over time. In addition, there may be a desire by some producers to change the way they supply markets e.g. an Engineer-to-Order (ETO) company might decide to move to a greater degree of BTO with less direct customer involvement in product design and engineering or it might decide to move towards a Mass Customization approach, offering greater potential product variety to the marketplace but doing so in an efficient way.

An open pipeline approach can contribute to a firm’s ability to meet customer demand in high variety situations and this may be further enhanced by allowing some degree of reconfiguration of products in the planning pipeline. In judging the applicability of open pipeline approaches a number of factors need to be considered - how extensive the planning pipeline is, how late in the planning pipeline a product specification can be changed, how product variety is realized in production and assembly and whether form postponement in production is feasible and desirable. If form postponement within production is technically feasible, can be done cost effectively and offers the level of variety and customization that is needed to satisfy customers then it may bring more stability in planning. As noted earlier however, it may be difficult to achieve and where an extensive planning pipeline exists it may offer little benefit.

An open planning pipeline should be considered when there are high levels of variety, an extensive planning pipeline and a heterogeneous customer base with a proportion of customers requiring specific product variants. It is important where pure MTS or pure BTO are unattractive either because of costs, risks or response times. A major advantage is that it brings flexibility to Build-to-Forecast production environments, whilst allowing a desired rate or level of production to be maintained. In such environments it is usually possible to allocate products from the planning pipeline in a dynamic manner. As well as the automotive sector, firms in machinery and capital equipment manufacture, instrumentation, computer servers, telecommunications and electronic equipment satisfy many of the requirements for open pipeline planning and the approach may therefore bring benefits in terms of order fulfillment. Fulfillment models of this type have been reported in machinery and capital equipment manufacture (Raturi et al. 1990, Bartezzaghi & Verganti 1995 a,b). There is interest also in adopting these forms of models in the house building sector, where there is growth in the use of factory based production (Housing Forum 2004, Winch 2003) and house customization (Barlow, 1999).

When a degree of reconfiguration in the pipeline is possible, the likelihood of finding a product that meets a customer's specification increases and the likelihood that the customer will need to compromise reduces. In any particular environment the potential to reconfigure products in the planning pipeline will be affected by technical, operational, cost and risk-related factors. In some sectors only upgrading of planned products may be possible (one way flexibility) whilst in others, planned products may have features removed as well as added (two way flexibility). Software-based product features for instance are likely to be amenable to flexibility in either upward or downward directions.

The costs associated with reconfiguration also have to be borne in mind. Product specification in upstream pipeline segments may be relatively open with respect to many features and changes in these features may incur negligible costs. A product at the most upstream position in a dynamic pipeline may have only minimal specification, essentially a capacity slot with no cost implications if specification changes are made. In the downstream pipeline segment close to production, changes to product specifications may be technically feasible but the operational costs may be prohibitively high for certain product features and particular kinds of modification or amendment e.g. because of supply issues or subsequent assembly balancing constraints or additional set up costs. The potential benefits with respect to improvements in fulfillment performance from reconfiguration in an open pipeline system must be balanced against the costs that may be incurred.

5. Conclusions

In this paper we have presented and described a new classification of production and order fulfillment approaches available to manufacturing companies that offer high variety and/or product customization. Six categories have been identified across a wide spectrum of approaches. Within this spectrum open pipeline planning has been highlighted as an important emerging approach that allows a customer order to be fulfilled from anywhere in the system. It combines fulfillment from finished stock, from the planning pipeline and by Build-to-Order. The links between the open pipeline approach, decoupling concepts and postponement strategies have been noted. The relevance of the approach to the volume automotive sector has been highlighted. When products can be reconfigured in the planning pipeline then additional benefits may be gained in terms of improved fulfillment performance and a reduction in customer compromise. Results from a simulation study have been presented illustrating the potential benefits from reconfiguration. The application of open pipeline concepts to different manufacturing domains has been discussed and the operating characteristics of most relevance have been highlighted. In addition to automotive, sectors such as machinery and instrumentation, computer servers, telecommunications and electronic equipment may benefit from an open pipeline planning approach. When properly designed these systems can significantly enhance order fulfillment performance.

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