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Virtual-Build-to-Order as a Mass Customization Order Fulfilment Model

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Abstract: Virtual-build-to-order (VBTO) is a form of order fulfilment system in which the producer has the ability to search across the entire pipeline of finished stock, products in production and those in the production plan, in order to find the best product for a customer. It is a system design that is attractive to Mass Customizers, such as those in the automotive sector, whose manufacturing lead time exceeds their customers' tolerable waiting times, and for whom the holding of partly-finished stocks at a fixed decoupling point is unattractive or unworkable. This paper describes and develops the operational concepts that underpin VBTO, in particular the concepts of reconfiguration flexibility and customer aversion to waiting. Reconfiguration is the process of changing a product's specification at any point along the order fulfilment pipeline. The extent to which an order fulfilment system is flexible or inflexible reveals itself in the reconfiguration cost curve, of which there are four basic types. The operational features of the generic VBTO system are described and simulation is used to study its behaviour and performance. The concepts of *reconfiguration flexibility* and *floating decoupling point* are introduced and discussed.

1. Introduction

The trend of increasing product variety is stimulating not only fresh examination of business strategies such as Mass Customization but also the design of new order fulfilment systems to deliver high levels of customer-focused variety. For example, the principles of postponement and operations reversal are two approaches that are receiving attention as a result of the challenges of producing greater amounts of variety and the demands for ever-shortening lead times [e.g. 1, 2, 3, 4, 5]. In the context of mass customized computer servers a methodology is developed in [6] and [7] for optimising the use of an inventory of partly-assembled products, referred to as vanilla boxes, to reduce lead time. However, producers of capital goods and high-ticket items, most notably automotive vehicle manufacturers, are reluctant to employ mid-process inventories, being keen on the principles of lean manufacture, an objective of which is to strive for continuous processes with zero or minimal buffers. Furthermore, the competitive market place and continual pressure on production costs translate into the need for manufacturing facilities to be highly utilised. Nevertheless, these sectors are faced also with the challenge of increasing product variety. In the medium term the variety envelope may be stable, but in the short term the variety through manufacture must be shaped by customer orders [8]. In addition, the market for products is multi-faceted, consisting of many types of customers with differing requirements and priorities. Some customers will be seeking immediate fulfilment while others will be planning ahead. Some will be rigid in their choice of specification while others will be flexible and willing to accept specification compromise.

Given their reluctance to tolerate inventory, enterprises in these sectors need other approaches to cope with the complexity of the business environment and market place. Rather than use inventory they could

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develop appropriate process flexibilities, such as the ability to tolerate greater sequence variation through assembly flow lines with minimal cost overheads [9, 10]? A further tactic is to take advantage of the magnitude of their operations, in particular to develop the ability to fulfil customers from any portion of inventory regardless of where it is located geographically or its form – whether finished products, part-finished or not yet manufactured. The name given to such an approach to order fulfilment is Virtual-Build-to-Order (VBTO). In the context of automotive operations it is described as connecting customers 'either via the internet or in dealer's showrooms, to the vast, albeit far-flung, array of cars already in existence, including vehicles on dealer's lots, in transit, on an assembly line, and scheduled for production', with the expectation that 'customers are likely to find a vehicle with the colour and options they most want' [11] and reflects current practice across the major automotive OEMs

A fundamental capability for a VBTO system is the ability to search the order fulfilment *pipeline* on behalf of a customer. The pipeline is the full set of unsold finished stock and unallocated production orders, physical and planned (the virtual component). Because product can be allocated to a customer from any point along the pipeline, the VBTO system could be termed a *floating decoupling point* system. A second capability that is desirable in VBTO is the ability to *reconfigure* a product in the pipeline – i.e. change its specification to reduce or remove differences between it and the customer's preferred specification. Some reconfigurations may be possible once the product has left the factory, which is equivalent to *form customization* as defined by [12]. More extensive reconfigurations – labelled *optional customization* by [12] - are likely to be more feasible the earlier the product is in the production plan.

The abilities to search the pipeline and to reconfigure products offer the opportunity to eliminate or at least reduce the number of specification compromises made by customers than would be the case if they were limited to the choice on offer in a local warehouse, and to deliver in shorter lead times than would be the case in a full-blown BTO system. Essentially VBTO enables the extensive variety that exists in physical and virtual product pipelines be exploited more effectively by the producer for customer benefit and provides a model for a type of mass Customization.

This paper describes the features of a generic VBTO system and uses simulation to study aspects of its behaviour. In particular it focuses on the impact of reconfiguration costs, customer aversion to waiting and mismatches between the variety envelope produced and that demanded by customers. The need for reconfiguration flexibility in Mass customization systems is highlighted.

2. VBTO system description

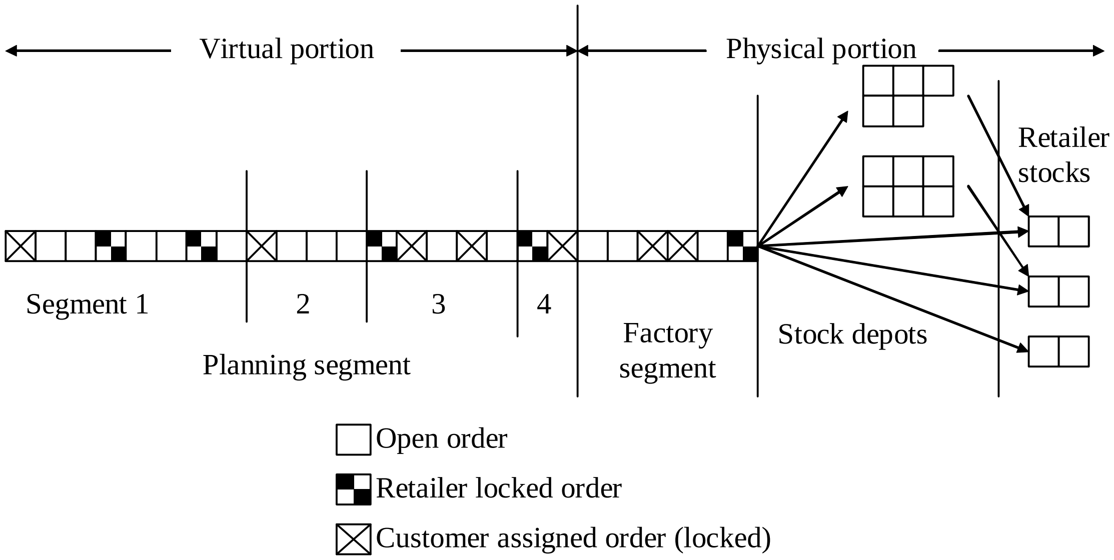
2.1. Structure

In a VBTO system the order fulfilment pipeline can be conceived of as a series of *segments* (Figure 1). The final segment is the stock held at each retailer *(retailer stock)*, which may come via *stock depots* or direct from the *factory segment*. The finished stock and manufacturing segments make up the *physical* portion of the pipeline, upstream of which is the *virtual* portion which itself may be divided into several segments. The virtual segment of the pipeline is the *production plan.* The separate segments of the virtual portion of the pipeline are determined by the firmness and constraints on the production plan - as a product order moves from one segment to another its specification becomes frozen. The orders in the final virtual segment are frozen and cannot be changed in terms of specification or sequence.

The diagram shows three types of orders moving through the pipeline. Both customer assigned orders and retailer locked orders go directly to the retailer from the manufacturing segment and are not available to be re-allocated. Hence only open orders reside in the stock depots.

Interpreting the pipeline in terms of a typical automotive pipeline, the factory segment is the assembly plant and the production plan is communicated to suppliers who then prepare to feed components to the plant in the required sequence.

Figure 1: Pipeline segments of a VBTO system



2.2. Operation

The generic operational characteristics of VBTO systems are:

- all products enter the pipeline with a full specification and will be manufactured to that specification if not modified;
- until a product is assigned to a customer or locked by a retailer, it is available to other retailers and customers. Retailers can lock an order when in need of a display or demonstration model;
- a customer can be fulfilled by a product
  - taken from finished stock,
  - taken from the pipeline that matches the required specification,
  - taken from the pipeline that is reconfigured in some way to match the specification,
  - that is entered at the start of the pipeline i.e. a Built-to-Order (BTO) product.

When implementing a VBTO system, an enterprise may create rules for how products are selected for customers, perhaps due to assembly sequencing constraints or component capacity limits. Another concern could be the cost of reconfiguration (see below) for which a maximum threshold could be set. Constraints such as these can lead to a dealer or customer having to be fulfilled by a BTO product rather than from one that is found in, or reconfigured from the pipeline.

2.3. Reconfiguration

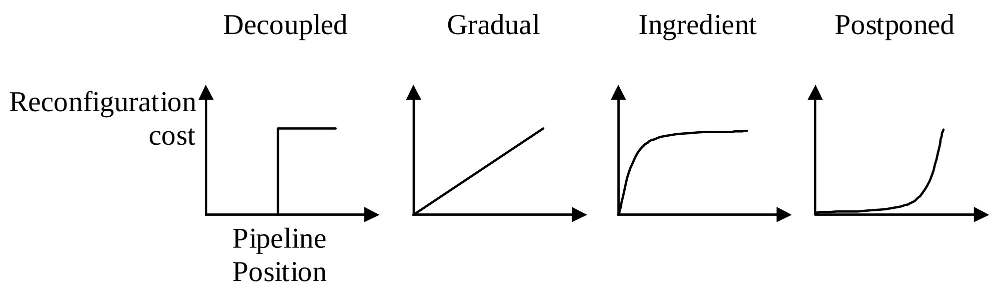
Reconfiguration is the process of changing a product's specification as it progresses along the pipeline. Depending on the point the product has reached the consequence of reconfiguring it could be no more than the future production plan being amended, or it could mean that components that have been made already must be stored or scrapped and a replacement set sourced or manufactured, or it could mean that a part or module that has been fitted to a product is removed and swapped with another from a stand-by stock that is held in readiness for such a situation.

The cost of reconfiguring a product can be expected to be dependent in part on pipeline position. This cost component can be plotted against pipeline position as a *reconfiguration cost curve*. Four signature reconfiguration cost curves can be envisaged (Figure 2):

- Decoupled: a feature or product starts as generic but then at a point along the process becomes a specific variant, after which the cost of changing the specification is high;
- Gradual: as a feature or product progresses along the pipeline the cost of changing the specification increases steadily;
- Ingredient: from an early point along the pipeline the cost of changing the specification is high which can be due to the identity of the product being strongly dependent on its constituents and having low commonality with other variants in the product range;
- Postponed: not until late in the pipeline does the cost of specification change become significant.

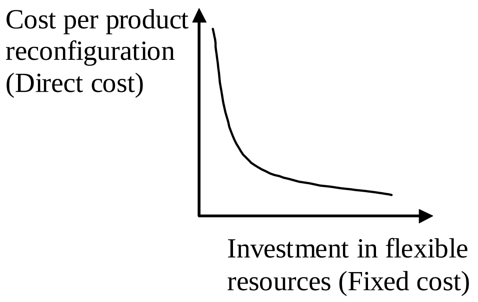
If a product is constructed from several features, their reconfiguration cost curves can be independent, especially if the supply resources necessary for their realisation are separate and independent. Consequently one feature can have a 'postponed' shape and another feature an 'ingredient' shape, while another has a 'gradual' shape, and so on.

Figure 2: Signature reconfiguration cost curves



The component of reconfiguration cost represented by the reconfiguration cost curve may be viewed as a direct cost that is incurred only when a product is reconfigured. There is a second component of reconfiguration cost – the fixed cost of investing in the flexibility to enable reconfiguration. The two cost components can be expected to be closely related, i.e. the greater the investment in flexibility, the lower will be the direct cost (Figure 3). The objective of an enterprise is neither to over-invest nor under-invest in resources to enable reconfiguration. For example, it would be undesirable if an enterprise reduced the cost of reconfiguration through investment, only for the sales function to persuade customers to compromise on their specification. In the same vein, if the cost of reconfiguration is high it would be inadvisable for a customization service to be over-played to customers.

Figure 3: Conceptual relationship between reconfiguration direct costs and investment in flexible resources



2.4. Customer aversion to waiting

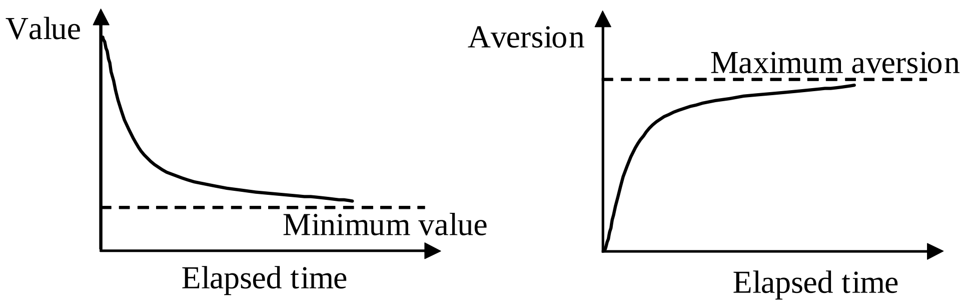
Differences across customers are, of course, the prime reason for the growth in product variety. However, customer differences also create other forms of 'service' variety that can potentially be satisfied through the order fulfillment system. In particular customers vary in their degree of sensitivity to waiting time for products and to product price. Price and lead-time are interrelated. Price is connected to value [13] and it is well understood that value tends to decay over time [14]. However, the rate of decay is not uniform across customer groups and, furthermore, for some customers delivery earlier than an agreed date is undesirable.

Methodologies for exploiting customer differences are now emerging under the banner of yield management (also known as revenue management) and its proponents see many opportunities for exploiting its principles [15] in a wide range of sectors but the research relevant to BTO operations is scarce.

The principle of value decay (Figure 4 left graph) can be transformed into an aversion to waiting factor (Figure 4 right graph). This allows the attractiveness of a product to a customer to be related to the product's pipeline position. If a customer has a choice of two identical products, one early in the pipeline, one almost at the end of the pipeline, their preference will be for the later product.

Within VBTO systems, the effect of the aversion to waiting factor is to force the enterprise to either allocate products from the downstream end of the pipeline, even if a high reconfiguration cost has to be incurred, or to offer price incentives to tempt the customer to wait or accept specification compromise. Consequently, because the strength of aversion to waiting varies between customers, it is advantageous to the enterprise to take account of each customer's strength of aversion when searching the pipeline. For those with a low aversion the enterprise can favour products from the early part of the pipeline, and reserve the later sections of the pipeline for customers with a strong aversion to waiting.

Figure 4: Correspondence between value decay and aversion to waiting



3. Simulation study

We have developed a discrete event simulation environment to study the behaviour of VBTO systems. The model captures the principal VBTO structural and operational characteristics described above. The simulated VBTO system has a pipeline feeding a stock of finished products. The rate of production is constant and equal to the customer arrival rate that is also assumed constant. The product has four independent features (A, B, C, D) and each feature has four options, giving a total of 256 possible variants. The customer demand is assumed random and uncorrelated, and the feed of unallocated products into the pipeline is also random and uncorrelated. As each customer arrives, a search is performed of the stock and of the pipeline and if a suitable product is found it is allocated to the customer and made unavailable to other customers. The study reported here investigates the impact of the imposition of limits on the reconfiguration cost tolerated by the producer and shifts in the customer demand on reconfiguration cost and customer waiting times. Before the results of the study are presented, the methods used in the simulation to model the reconfiguration cost, customer aversion to waiting and the fulfilment procedure are described.

3.1. Operationalising the VBTO system in a simulation model

Reconfiguration cost

Reconfiguration cost is operationalised as an additional cost, the magnitude of which is dependent on the position along the pipeline of the product that is being reconfigured and how many features of the product are being re-specified. The algorithm for calculating reconfiguration cost is given in equation [1]. It generates a value greater than 1. For example, a value of 1.08 indicates that to reconfigure the product will add 8% to the cost compared to a non-reconfigured product.

$$RCM_j = {}_{i=1}\Sigma^{n} (\delta c_{ij} \text{ x } fc_i) + 1 \qquad [1]$$

RCM_j is the Reconfiguration cost multiplier for product in position j of the pipeline

δc_{ij}, the fractional cost increase of reconfiguring feature i at position j of the pipeline

fc_i, the fraction of cost that feature i is of the total product (in the simulation study the four features are of equal proportion, i.e. each is 25% of the cost of the product).

n is the number of features in the product

The value of δc is defined by the feature's *reconfiguration cost curve*. In this simulation study each feature (A, B, C, D) has an independent cost curve of different degrees of postponement (Figure 5). These reconfiguration cost curves allow for two types of reconfiguration: *cost incurring* reconfiguration and *costless* reconfigurations. In the schematic, until a product reaches the fifth position along the pipeline it can be reconfigured without additional cost. Between the fifth and tenth positions, changing the specification for feature A incurs additional cost in a linear fashion, but there is no cost for changing the three other features. Between the tenth and fifteenth positions changing feature B also incurs additional cost. Products further along the pipeline become liable for additional cost when changing feature C and lastly for feature D. At the end of the pipeline is a locked zone in which no product can be reconfigured. The parameters of the reconfiguration cost curves used in the simulation for each feature are summarised in Table 1. It assumes a fixed pipeline length of 90.

Note should be taken that in this simulated system reconfiguration cost does not depend on the number of options in a feature, or on how different one option is from another. Hence, reconfiguring a feature from option 3 to option 1 incurs the same cost as reconfiguring from option 2 to option 3, or from option 4 to option 1, and so on.

Figure 5: Schematic of reconfiguration cost curves for the four features

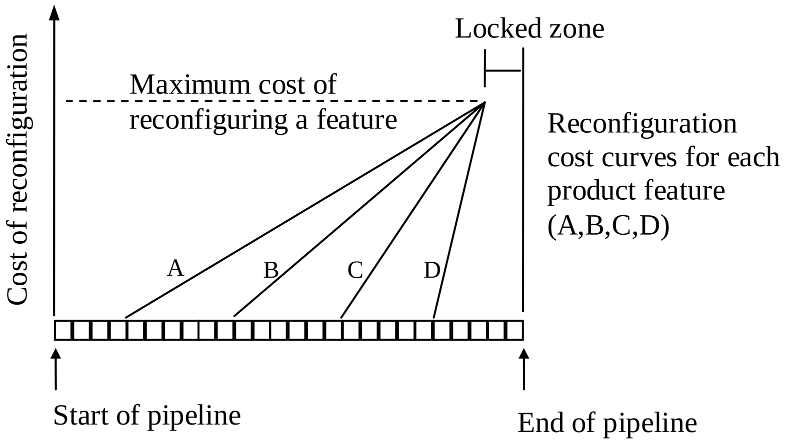


Table 1: Summary of product feature parameters (note the Pipeline length is 90)

Feature	Maximum fractional cost increase (δc) of reconfiguring the feature	Reconfiguration cost curve start position	Reconfiguration cost curve end position
A	2	10	80
B	2	30	80
C	2	50	80
D	2	70	80

Customer delay aversion

Aversion to waiting is modelled as an exponential function, with the *decay rate facto*r and *maximum decay* being control variables [2].

$$da_{pq} = m_p - \mathrm{Exp}(df_p\,(L - p_q + 1)(m_p - 1)) \qquad [2]$$

da_{pq} is the delay aversion factor of product in position q for customer type p

m_p is the maximum delay aversion for customer type p

df_p is the decay rate factor for the customer type p

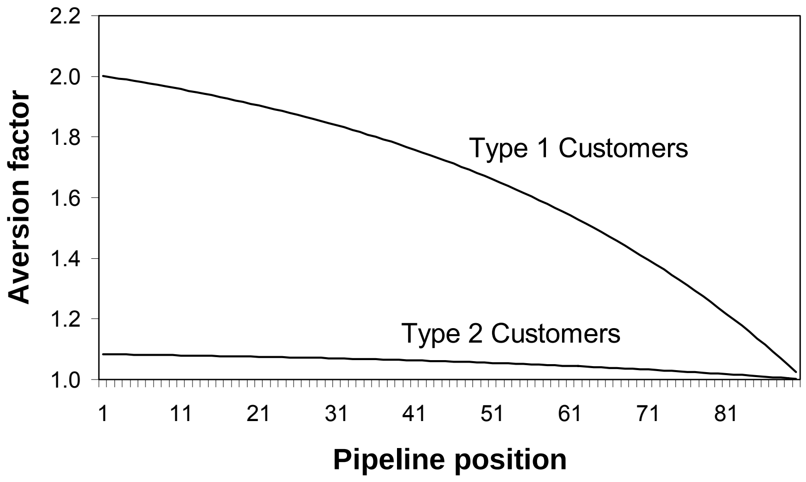
L is the length of the pipeline

p_q is the position of product q along the pipeline

A product in the last position on the pipeline (i.e. when p = L) has a delay aversion >1. This is because it has one time period to elapse before it can be delivered to the customer. Products in stock have a delay aversion factor of 1.

Two types of customer are modelled in the simulation. They have the same decay rate factor (df) which is set to -0.02 and different maximum delay aversion (m) or 2.2 for Type 1 and 1.1 for Type 2 customers. The delay aversion factor for the two customer types is plotted in Figure 6.

Figure 6: Delay aversion factor (da) for Type 1 and Type 2 customers



Fulfilment procedure

Customers are fulfilled in one of four ways: by a product from stock; by a product that is an exact match found in the pipeline; by a product from the pipeline that is reconfigured; or by a product being Built-to-Order that is inserted at the start of the pipeline. The logic in the simulation model decides which order fulfilment route is used for each customer at the time of their arrival.

When searching for a product for a customer, the simulation searches for the product with the *minimum index value*, with the index being the product of the reconfiguration cost multiplier and the delay aversion factor:

$$\text{Index}_{rs} = \text{RCM}_s \text{ x } \text{da}_{rs} \quad [3]$$

Index_{rs} is the index value of the product in pipeline position s for the customer type r

RCM_s is the Reconfiguration cost multiplier for product in position s of the pipeline

da_{rs} is the delay aversion factor of a product at position s for customer type r

Two or more products can have the same reconfiguration cost multiplier, in which case the product chosen for the customer will be the one with the lower delay aversion factor. Consequently, a stock product with an exact specification match is always selected in preference to a pipeline product. Note, a product in the pipeline requiring reconfiguration to match a customer may have a lower index than a product with an exact specification match that is further upstream.

A *maximum tolerated reconfiguration cost* can be set. Consequently, if no exact match can be found and no product can be reconfigured for less than the maximum tolerable cost, a request is sent to the start of the pipeline for a product to be Built-to-Order. This is the only condition in the simulation study that would result in a customer being fulfilled by the BTO method.

3.2. Experimental conditions

The simulation has been analysed as a non-terminating system. At the start of each simulation run the pipeline is primed with products. A warm-up period of 400 customers is discarded and then the method of batch-means [16] has been used for calculating statistics, with 9 batches of 300 customers with a ‘dead’ period of 50 customers between each batch. The statistics from the 9 batches are combined to calculate the performance metrics for the experimental condition.

The specification of each product entering the pipeline is generated from random uniform distributions, with each feature linked to a separate random number stream. The two types of customer are in equal proportion and they arrive in random sequence. As for products, each feature of a customer's specification is linked to a separate random number stream. Customer inter-arrival time is fixed and equal to the production rate.

To assist in the comparison of the VBTO system conditions, the variance reduction method of Common Random Numbers has been used [16].

The following performance metrics are collected:

- average waiting time for both customer types. This is presented as a percentage of the pipeline length, hence a waiting time of 100% translates to 90 time periods. (Note: when fulfilled from stock the waiting time is zero);
- average proportion of both customer types fulfilled by each method (e.g. by BTO, reconfigured product, from stock);
- average cost of fulfilment for both customer types.

3.3. Results

Limit on reconfiguration cost

A limit on the cost of configuration tolerated by the producer is introduced, and the effect of lowering the limit is studied. Gradually lowering the maximum tolerated reconfiguration cost has little effect on the fulfilment metrics for the customer segment that is less averse to waiting (Type 2) but has a great effect on Type 1 customers. Figure 7 shows how the average fulfilment cost multiplier for Type 1 customers drops markedly as the limit on reconfiguration cost is lowered (from 1.6 to 1.01). The limit on cost does not alter the proportion of either customer type fulfilled by reconfigured products which remains at just above 80%, but it shifts towards costless reconfigurations (Figure 8). The waiting time for both customer types increases, with waiting time for Type 1 customers rising by 50% when comparing the cost limits of 1.5 and 1.01 and by 10% for Type 2 customers (Figure 9). These results indicate that a limit of between 1.2 and 1.3 on the reconfiguration cost reduces fulfilment cost with little detriment to waiting time.

Figure 7: Average reconfiguration cost multiplier for Type 1 and Type 2 customers, at eight different limits on reconfiguration cost

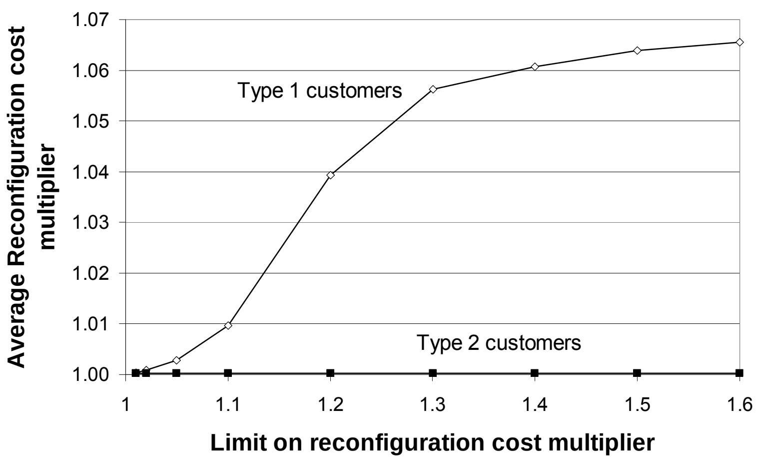


Figure 8: Proportions of Type 1 and Type 2 customers reconfigured with and without cost at eight different limits on reconfiguration cost

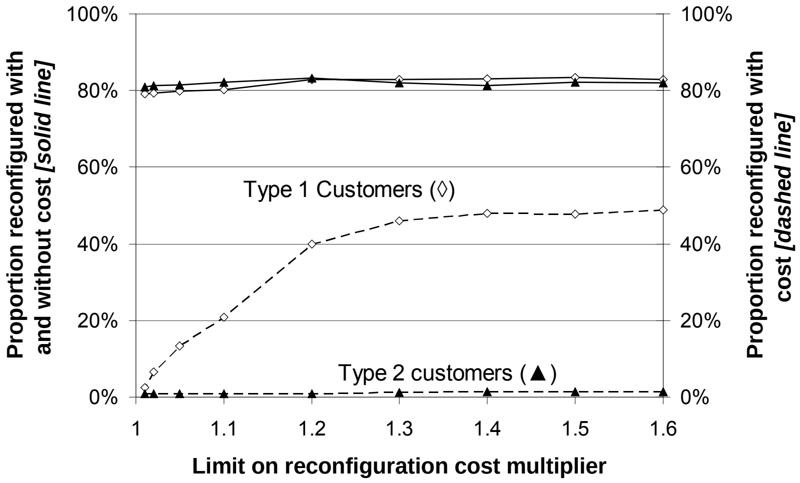
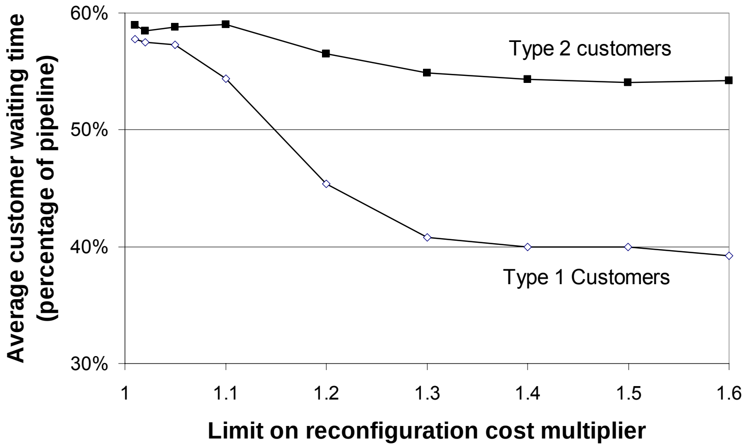


Figure 9: Waiting time for Type 1 and Type 2 customers, at eight different limits on reconfiguration cost



Customer mix

Varying the mix of the two customer types reveal how products that are already allocated to customers interfere with the search for products for subsequent customers. There are two forms of interference: interference between customers of the same type, and interference between customers of different types. The former – interference between customers of the same type – is illustrated by Figure 10.

The average waiting time for Type 2 customers is at its lowest when there are few Type 2 customers. They are fulfilled from just before the mid point in the pipeline. As the proportion of Type 2 customers rises the availability of products in this zone will drop and the likelihood that there is a low cost match among these will also drop. Products further upstream will be cheaper on average to reconfigure but will be less attractive due to the customer's delay aversion factor. However, the shape of the aversion factor curve for Type 2 customers is almost flat (Figure 6) in this zone of the pipeline, hence the matching index in equation [3] is more sensitive to changes in reconfiguration cost than to changes in the aversion factor. Consequently, as the proportion of Type 2 customers rises, rather than incur higher fulfilment costs the search mechanism favours having the customers wait longer.

Type 1 customers, being more averse to waiting than Type 2 customers, are found products in the downstream part of the pipeline. It can be expected that Type 1 customers interfere with each other, but they are also interfered with by Type 2 customers, whose products come through this section of the pipeline. The interference from the other customer type has a stronger impact than the interference between Type 1 customers. Both the average fulfilment cost and average waiting time for Type 1 customers are lowest when there are no Type 2 customers (Figure 11). As the proportion of Type 2 increases the number of available products to Type 1 customers drops. Rather than incur high fulfilment costs, the producer would like to allocate products from further upstream. However, the gradient of the delay aversion factor for Type 1 customers is steep in this region of the pipeline (Figure 6) hence a reduction in fulfilment cost is countered by an increase in the delay aversion factor. The outcome is that both the producer and Type 1 customers compromise as the proportion of Type 1 declines, with fulfilment costs and waiting time increasing.

Figure 10: Waiting time and fulfilment cost multiplier for Type 2 customers as their proportion in the population varies

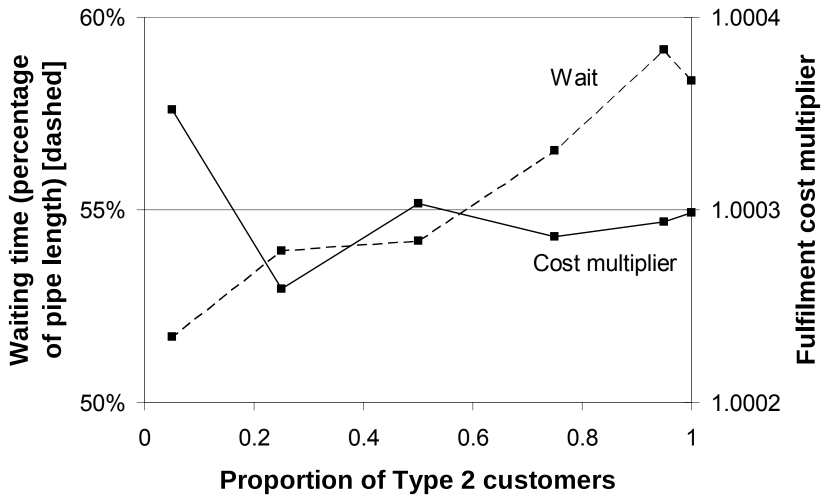
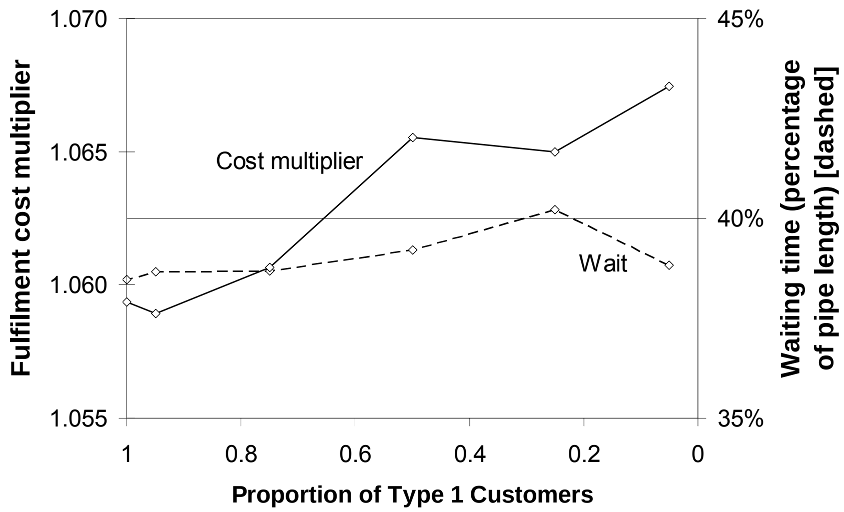


Figure 11: Waiting time and fulfilment cost multiplier for Type 1 customers as their proportion in the population varies



Mismatch between produced and demanded variety

In this section a discrepancy is introduced between the variety demanded by customers and the variety being manufactured. The random sequence of products feeding into the pipeline remains as before with all variants having equal probability of being the next product. The variety demanded by customers is altered with a skew introduced. Five levels of skew are studied (Table 2). To clarify, in the first condition the probability of a customer seeking option 1 of each feature is lowered to 23.5% whereas 25% of products entering the pipeline have this option for each feature. The discrepancy for option 1 is therefore 1.5%. The sum of discrepancies for the four options is 4% in the first condition.

Table 2: Probability of each option in five levels of discrepancy between customer demanded variety and produced variety

Discrepancy	Probability of each option			
	1	2	3	4
O%	0.25	0.25	0.25	0.25
4%	0.235	0.245	0.255	0.265
8%	0.22	0.24	0.26	0.28
16%	0.19	0.23	0.27	0.31
24%	0.16	0.22	0.28	0.34
32%	0.13	0.21	0.29	0.37

As the mismatch between the distribution of produced products and customer demanded products increases the waiting time for customers is affected more than the cost of fulfilment. The greater the discrepancy the greater the waiting times for both customer types (Table 3). The pattern of impact on fulfilment cost is different (Table 4). The cost of fulfilling Type 1 customers who are strongly averse to waiting is little changed at first and then drops markedly at the highest discrepancy. As the discrepancy rises, it is more likely not only that the proportion of customers fulfilled by reconfigured products rises (Figure 12) but that products in the pipeline will need to have more features reconfigured. The cost of reconfiguration has a greater bearing on the matching index in equation [3] and this leads to products with the minimum index being found further upstream than before.

When the discrepancy is on one feature only the pattern of impact is different. When the greatest discrepancy is on feature A, which is the least postponed feature, the average fulfilment cost rises to a higher level than for any of the conditions with all features experiencing a discrepancy. The impact on waiting time is also strong but does not exceed the other conditions in the same way as for the cost. The feature A discrepancy impacts Type 1 customers more so than Type 2 but both are impacted in regard to waiting time. When the greatest discrepancy is on feature D, the most postponed feature, the impact is considerably less than with feature A and less than all other conditions investigated bar the first.

Figure 12: Proportion of customers fulfilled through reconfiguration

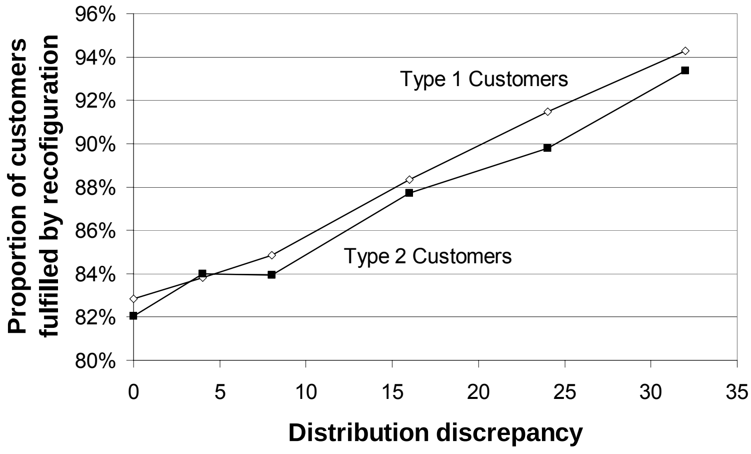


Table 3: Impact of distribution discrepancies on average waiting time

Condition	Discrepancy	Waiting time (compared to 'standard')		
		All	Type 1	Type 2
1	4%	104%	104%	104%
2	8%	105%	105%	105%
3	16%	116%	117%	114%
4	24%	126%	132%	122%
5	32%	144%	155%	137%
6	32% Feature A only	123%	123%	124%
7	32% Feature D only	102%	102%	102%

Table 4: Impact of distribution discrepancies on average fulfilment cost multiplier

Condition	Discrepancy	Change in cost multiplier (compared to 'standard')		
		All	Type 1	Type 2
1	4%	99%	99%	89%
2	8%	102%	103%	82%
3	16%	104%	104%	83%
4	24%	97%	97%	71%
5	32%	78%	78%	40%
6	32% Feature A only	122%	122%	83%
7	32% Feature D only	97%	97%	94%

4. Discussion

The VBTO system is relevant to situations in which the envelope of product variety is high or very high and beyond the scope of variety that can be held in stock or produced in a short timescale. In this study it is assumed no customer tolerates compromise in the specification of their product, but that customers differ in their tolerance of waiting time. If the order fulfilment system allows for products to be reconfigured as they progress along the pipeline and the cost of reconfiguration is not negligible, the more willing the producer is to incur additional costs from reconfiguration, the greater the scope the producer has to segment customers. This is shown in the first study when a limit is placed on the reconfiguration cost and demonstrated that as the limit is lowered, the fulfilment metrics for the two customer types converge.

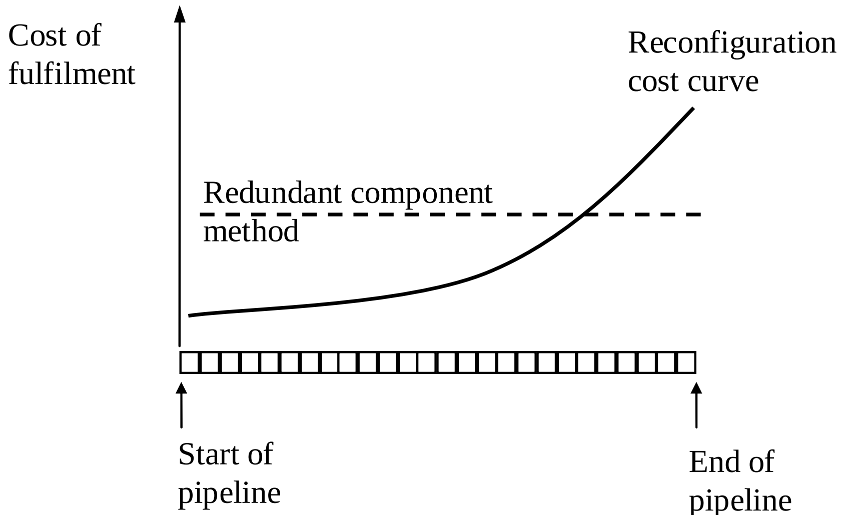
The performance of the VBTO system is sensitive to external conditions as shown in the studies of customer proportions and variety mismatch. In both situations the strength of the effects on waiting time and fulfilment cost would be different if the customer delay aversion functions were altered. The functions used in this study are arbitrary and although the theory of exponential value decay underpins them, it is probable that an enterprise should set them using a combination of empirical evidence and management judgement.

A key contribution of this study is the concept of reconfiguration flexibility and its operationalisation in the form of the reconfiguration cost curve. Flexibility, in one guise or another, is a pre-requisite for the MC strategy to succeed [17]. Some have spoken of the need for reconfigurable manufacturing resources [18, 19] and modifiable order fulfilment processes [20] and others have talked of the ability to physically reconfigure products as a route to MC [21]. The concept of reconfiguration flexibility goes beyond these specific approaches and provides an overarching framework for flexibility in the MC context. Although many types and taxonomies of flexibility can be found in the literature, it is also common to read the observation that flexibility is context specific and that definitions and measures of flexibility that suit one environment can be ill-suited to another [22]. Even though several types of flexibility that on first reading appear suitable for characterising MC systems, such as mix flexibility and scope flexibility, it is argued here that the concept of reconfiguration flexibility more fully encapsulates the flexibility needs of MC systems. In particular it captures the qualities required of order fulfilment systems in which there is no distinct decoupling point, but in which the decoupling point *floats* along the pipeline, for which we have coined the term *floating decoupling point system*. The VBTO system analysed in this paper is a floating decoupling point system.

The reconfiguration cost curve captures the key aspects of the reconfiguration flexibility concept. Quantifying such cost curve allows MC systems to be compared on a common basis and hence allows the development of a standard methodology for analysing and appraising investment and operational decisions. The quantification of the reconfiguration cost curve opens the way for operational trade-offs to be studied. For instance, as noted in [6] it may be cost effective for a producer in a high variety environment to substitute higher grade components or to leave redundant components in the product rather than lose the customer. These two strategies could be used as to reconfiguring a product to be an exact specification match. From a cost perspective it may be found that there is point along the pipeline at which it switches from being cost effective to reconfigure a product, to being cost effective to use one of these alternative tactics, illustrated conceptually in Figure 13**.** In an MC system in which the variety in the pipeline is changing and products are being allocated to customers continually, the solution to the 'best' product for a customer will need be recalculated dynamically, and hence the product allocation algorithms would need to be embedded into the control system.

The current work of the authors is investigating further aspects of the performance of VBTO strategies and their implications for Mass Customization.

Figure 13: Comparison of fulfilment methods



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