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Mass Customization: fundamental modes of operation and study of an order fulfilment model

by

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Abstract

This research studies Mass Customization as an operations strategy and model. Opinions differ over whether MC should be a label for a specific business model in which customers select from pre-engineered product options, or whether it should be interpreted as a performance goal that has wider relevance. In this research it is viewed as the latter and a manufacturing enterprise is considered to be a mass customizer if it gives its customers the opportunity to have a product any time they want it, anywhere they want it, any way they want it and in any volume they want it, and at the same time brings the benefits that are associated with mass operations, in particular those of price and quality

In the literature MC is not one operations strategy but a family of sub-strategies and there are several classification schemes, most of which delineate the sub-strategies by the point along the value chain that customization takes place. Other than for one scheme for which correlations between technologies and MC types has been sought by means of a survey, no progress has been made in developing operations configurations models.

Through the study of primary and secondary case studies several classification schemes are appraised and a new framework of five fundamental operations Modes is developed. The Modes are the kernel of a theory of MC, with the other elements being:

- A model for Mode selection that uses four factors to determine when a Mode is suitable;
- Indicative models of the information infrastructures of two Modes that demonstrate the Modes to be different and that they can be a foundation for configurations models;
- A set of product customizable attributes that reveals the multifaceted nature of customization and extends the terminology of customization;
- The ∂V (delta Value) concept that links the motivation for customizing attributes to differences between customers.

A theory of MC is proposed, which postulates:

- An MC strategy is relevant when there are differences across customers in how they value the configurations of customizable attributes;
- There are five operational sub-strategies of MC;
- The choice of sub-strategy for an enterprise is contingent on its organisation and its business environment.

One of the five modes, Catalogue MC, is the Mode that is commonly associated with MC. It is the Mode in which all product variants are fully engineered before being ordered. A diverse set of order fulfilment models of relevance to this Mode are reviewed and organised into four types: fulfilment from stock; fulfilment from a single decoupling point; fulfilment from several decoupling points; and fulfilment from a floating decoupling point. The term *floating decoupling point* is coined to describe systems that can allocate a product to a customer wherever the product lies, whether it be a finished product in stock, a part processed product or a product that does not yet exist but is in the production plan. In the automotive sector this system has been called Virtual-Build-to-Order (VBTO) and in this research the generic characteristics of VBTO systems are described and key concepts developed, in particular the concept of reconfiguration flexibility.

Discrete event simulation and Markov models are developed to study the behaviour of the VBTO fulfilment model. The non-dimensional ratio of product variety / pipeline length is identified to be a fundamental indicator of performance. By comparing the VBTO system to a conventional system that can fulfil a customer from stock or by BTO only, the role of pipeline fulfilment is identified and a surprising observation is that it can cause stock levels and average customer waiting time to be higher than in a conventional system. The study examines also how customer differences, in particular their willingness to compromise and their aversion to waiting, affect fulfilment and how fulfilment is dependent on reconfiguration flexibility.

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List of publications

Journal papers - published

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MacCarthy, B.L., Brabazon, P.G. & Bramham, J. (2003) "Fundamental modes of operation for mass customization", *International Journal of Production Economics*, **85** (3) 289-304.

Journal papers – in development

MacCarthy, B.L. & Brabazon, P.G. "Mass customization and quality: the relevance of standard quality techniques".

Book chapters

Brabazon, P.G. & MacCarthy, B.L. (2006) "Order fulfilment models for the Catalogue mode of mass customization – a review", In: Blecker, T and Friedrich, G (eds). *Mass Customization Challenges and Solutions*, International Series in Operations Research & Management Science, New York: Springer 211-232

MacCarthy, B.L., Brabazon, P.G. & Bramham, J. (2003) "Examination of mass customization through field evidence", In: Tseng, M.M. and Piller, F. (eds). *The Customer Centric Enterprise: Advances in Mass Customization and Personalization*, New York: Springer 19-33

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Brabazon, P.G. & MacCarthy, B.L. (2004) "Fundamental behaviour of Virtual-Build-to-Order systems", *Thirteenth International Working Seminar on Production Economics*, Igls, Innsbruck.

[2]Brabazon, P.G. & MacCarthy, B.L. (2003) "Virtual-build-to-order as an order fulfilment model for mass customization: context and model development", *2nd World Congress on Mass Customisation and Personalisation*, Munich.

MacCarthy, B.L., Brabazon, P.G. & Bramham, J. (2001) "Suitability of common quality assurance and quality control systems and practices for mass customisation operations", *2001 World Congress on Mass Customisation and Personalisation*, Hong Kong.

MacCarthy, B.L., Bramham, J. & Brabazon, P.G. (2001) "Examination of mass customisation through field evidence", *2001 World Congress on Mass Customisation and Personalisation*, Hong Kong.

MacCarthy, B.L., Brabazon, P.G. & Bramham, J. (2001) "Mass customisation: alternatives to using product modularity as a route to mass customisation", *16th International Conference on Production Research*, Prague, Czech Republic.

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[2] Received the 'Best Paper' award

Chapter 1
Introduction

1.1 The emergence of Mass Customization

Stan Davis, styled by his publishers as a 'futurist', coined the term Mass Customization (MC[3]) in the 1980's (Davis 1987). He didn't offer a formal definition but to conjure its meaning he gave the example of 5000 mass produced shirts and asked:

> *"What if technology made it possible for every one of the 5000 shirts to be customized while on the factory assembly line, that is to say produced just as quickly as the 5000 identical shirts, yet at no greater expense?"*

When Davis first wrote of MC he presented it as a revolutionary and distant strategy, but from quality and economic perspectives it can be argued Davis was plotting the evolutionary course of manufacturing.

The aim of satisfying each customer is, of course, the raison d'être of quality management (see Table 1:1). Since the *customization* element of MC is about providing each customer with a product that is right for them, MC can be interpreted as a quality initiative.

Table 1:1 Quality definitions, adapted from Hassan *et al* (2000)

Source	Definition
Juran	Fitness for use. Conformance to specifications
Crosby	Conformance to requirements
Feigenbaum	Total composite . . . will meet the expectations of customers
Deming	Aims at the needs of the customer, present and future
ISO 9000	Totality of features and characteristics of a product or service . . to satisfy stated or implied need

If MC is in tune with the aims of the quality movement, should MC or similar concepts not be heralded in the quality literature? The quality literature is not entirely silent. Kolarik (1995) for example, sees a new quality paradigm emerging - *techno-craft* - that is MC in another guise. Techno-craft follows on from *custom craft*, *mass production and sorting*, *statistical quality control*, and *total quality management*. Kolarik writes:

> *"The techno-craft paradigm is a new frontier in quality that seeks to emulate the custom-craft paradigm in performance but reduce cost and the delivery time .... In the techno-craft paradigm customers get exactly what they want."*

Although there is little other evidence of MC being championed by the quality fraternity, it was foreseen by Garvin (1987) in his influential article on competing on quality. Garvin judged that in some situations customers measure quality in terms of the number of features on offer:

> *"choice is quality; buyers may wish to customize or personalize their purchase."*

Without using the term mass customization Garvin referred to a starter motor manufacturer using the latest in flexible manufacturing technology to customize without having to price its products prohibitively, and he expected this strategy to grow in importance.

The economic perspective on product customization is that it adds value by shrinking the difference between desired and actual product specification (Lancaster 1990). At the heart of this economic

[3] The acronym MC will be used throughout the thesis for Mass Customization

argument is the concept of spatial product differentiation - customers seek products closest to their ideal point in the product space, and the value they give to a product is proportional to its distance from their ideal point in the space. When choosing from the products of a conventional manufacturer a customer is likely to find the products are a distance from their ideal point, whereas a customization enterprise is able to adjust its products to be closer to this point. Using this form of economic model, Dewan, Jing & Seidmann (2000) argue that in circumstances where a seller offers customized products, first movers gain market share and profits at the expense of the conventional seller.[4]

Joseph Pine took up the mantle of leading proponent for MC and published an influential book (Pine 1993a). About MC he stated:

> *"The goal is to develop, produce, market and deliver affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want"*

Pine argued in his book that markets with increasing turbulence are fertile territory for the new business paradigm of Mass Customization. Greater competition and heterogeneity of demand are two indicators of increasing turbulence in his model (reviewed later in section 2.1.4) and there is good evidence of both of these trends in recent years. In a survey of consumer goods Cox & Alm (1998) found variety had increased markedly (Table 1:2) and analysis of the UK Consumer Price Index (CPI) shows that the prices of many goods are decreasing (Table 1:3). The reductions are particularly striking compared to the changing cost of services: while the cost of a new car has dropped by 0.6%, the cost of servicing a car has increased by 62.7%; similarly, the cost of appliances has reduced by 26% while the cost of repairing them has increased by 49.3%.

Following Pine's book there was a flurry of articles by Pine and others in the management press that evangelised MC but went only a little way to fleshing out its operational implications (e.g. Gilmore 1993, Pine 1993 b, Pine *et al* 1993, Spira 1993). Nevertheless, interest in MC was sparked and since then there has been an upward trend in the rate of research publications on MC.

As the literature review will demonstrate, there are significant issues of debate and unanswered questions about defining MC, what it means in practice and how it can be achieved in particular contexts. In the first part of the research study reported in this thesis MC is investigated 'in the round' to determine more clearly what it means in the context of the contemporary manufacturing enterprise. This leads to the definition of a set of fundamental modes of operation for MC and a reconsideration of the concept of customization. The second part of the research study focuses in depth on order fulfilment in a specific but very important MC context - environments that have high levels of customer-focused variety and where there are, necessarily, extensive pipelines of planned and physical products - the Virtual Build-to-Order system. This is most clearly seen in the automotive context but has relevance to many 'high ticket' environments. The first part of the research presented in the thesis is based primarily on an empirical field study and an analysis of the literature whilst the second part is based primarily on detailed quantitative simulation and analytical studies.

[4] The model assumes that improvements in manufacturing flexibility allow MC without a significant loss of efficiency but at greater cost than standard manufacture. They include a '*diseconomies of scope*' factor to reflect the decreasing returns from flexibility and assume the internet reduces the *menu* cost of managing multiple prices to near zero, enabling real-time individualized pricing. Interestingly, the benefits disappear when competing sellers adopt customization, leading to all sellers 'over-customizing' to the detriment of their profits.

Table 1:2 Offerings in the market place (Cox & Alm 1998)

	Early 1970's	Late 1990's
Television screen sizes	5	15
Dental flosses	12	64
Trainer styles	5	285
Contact lens types	1	36
Bicycle types	8	31
New automotive models	140	260
Soft drinks	20	87
TV channels	5	185
Pain relievers	17	141
Magazine titles	339	790

Table 1:3 Consumer Price Index data for a selection of categories (ONS March 2005)

	1996	March 2005
New Cars	100	99.4
Garments	100	58.6
Major Appliances and small electric goods	100	74.0
Photographic, cinematographic and optical equipment	100	50.6
Games, toys and hobbies	100	70.0

1.2 Research goals and focus

As can be expected in the early phases of a new operations strategy, the questions 'what is it?' and 'does it exist' have received as much, if not more attention, as the question 'how is it done?'. This research focuses on the operational demands of MC, and in so doing touches all three questions.

The research has two specific goals. The first goal is to advance the understanding of configuration models (explained below) for MC. The second goal is to develop greater understanding of a particular order fulfilment model of relevance to an important class of MC environments – the Virtual Build-to-Order model.

1.2.1 Goal 1: Advancing the understanding of configurations models for Mass Customization

Once a strategy has been described and defined, the agenda for researchers in operations management shifts to the implementation of the strategy. Taking a positivist (Thietart 2001) view of the nature of the domain, researchers seek both generally applicable and explanatory relationships between practice and strategy. The establishment of dependencies between organisational characteristics, organisational strategy and the business environment leads to the development of configurations models (Bozarth & McDermott 1998). Configuration models provide understanding of the *content* of strategies (the organizational structures, process technologies etc. that are best in a particular environment) and the *process* of strategies (the sub-strategy that an enterprise should select and how they should go about implementing the strategy). The organisational characteristics addressed by a configuration model can encompass organisational structure, manufacturing process and control technology, design technology, supplier management, customer service techniques, quality management methods, and such like.

To achieve this goal of the research a theory-building approach is used (Remenyi *et al* 1998). The data comes from a diverse set of case studies that qualify as MC companies using a working definition:

Enterprises that give their customers the opportunity to have a product any time they want it, anywhere they want it, any way they want it and in any volume they want it, along with the benefits associated with mass operations.

In the literature there are several schemes for dividing MC into operational sub-strategies. By analysing the case studies it is argued that the perspectives of these schemes do not lend themselves to being strong foundations for configurations models.

The output from this first phase is the identification of the key factors that distinguish sub-types of MC enterprises. This understanding is then used to develop a framework with five fundamental operations modes of MC. In addition, a framework for selecting a mode is developed. The potential for developing the modes into configurations models is explored and illustrated.

1.2.2 Goal 2: Studying the VBTO model

The second phase of research is the detailed study of an order fulfilment model that is suitable for one of the MC modes - the *Catalogue MC* mode. For this phase, the research shifts from field based to laboratory based, and uses discrete event simulation and analytical modelling to build an understanding of the emerging fulfilment model called Virtual Build-to-Order (VBTO). The key feature of the VBTO model is that customers can be sold a product from anywhere in the supply chain: a product in a retailer's stock room, a product in a distribution warehouse, a product that is part manufactured, or even a product that is yet to be manufactured. The principles and characteristics of the VBTO model are grounded in practice, particularly automotive operations.

1.2.3 Research boundaries

This research focuses on the operations within a manufacturing enterprise for fulfilling orders for customized products. The research does not examine the marketing of these products or how they are designed, but does consider operational issues that arise from product design.

1.2.4 Research situation

In 2000 a three year joint research project between Nottingham and Oxford Universities began to study MC in collaboration with a number of manufacturers and other businesses interested in MC[5]. A substantial part of the research work reported here took place within that project. Since that project's end in the autumn of 2003, further research has been funded by the Nottingham Innovative Manufacturing Research Centre and Ford Motor Company (who had collaborated in the larger project).

1.3 Structure of the thesis

Chapters 2 to 5 present the field-based research into the operational Modes of MC, addressing the first goal of the research. The literature review in Chapter 2 is focused on the first goal of the research. It establishes that ideas about MC have developed since the concept was first described in the late 1980s, but with only limited progress being made towards a coherent theory of MC operations. The research methodology is described in Chapter 3. In Chapter 4 a new scheme for classifying MC operations Modes is created, justified and tested. Data from the field studies are used in Chapter 5 to develop a way of describing product customization in the form of customizable attributes.

Chapters 6 to 11 address the second research goal in which the VBTO order fulfilment model is investigated using simulation and analytical models. Chapter 6 presents a literature review that examines VBTO in the context of other fulfilment models being used for Mass Customization. VBTO is an emerging model and in Chapter 7 its generic features are described and important concepts defined and developed. Chapter 7 also describes the modelling approach and simulation environment. Chapters 8, 9 & 10 present simulation studies of VBTO systems of increasing complexity. A Markov model of the VBTO system is developed and studied in Chapter 11.

Conclusions from both stages of the research are drawn in Chapter 12.

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[5] EPSRC project GR/N11742/01, Mass Customization for Manufacturing Enterprises

Chapter 2
Review of MC operations strategy literature and research agenda

Abstract

This chapter is concerned with the first goal of the research, namely the advancing of the understanding of configuration models for Mass Customization. Relevant literature is reviewed and discussed, from which is developed a set of research questions.

2.1 Literature review

To identify the progress that has been made toward configurations models, the literature on MC is reviewed in respect of the following:

- how MC has been defined and interpreted;
- how MC has been classified into sub-strategies;
- the linkages that have been made between MC strategy and operational requirements;
- guidance on when to adopt MC and on which sub-strategy to choose;
- and lastly, how product customization is addressed in the literature.

2.1.1 Definitions and interpretations of Mass Customization

The promotion of MC as a new paradigm prompted some commentators and researchers to question whether it really was new and whether it had potential in practice. Spring & Dalrymple (2000) accepted that customization hadn't received much attention in the manufacturing strategy literature but argued that MC was not novel and had restricted applicability. Their analysis of an early and well known case study by Kotha (1995) about the Japanese bicycle company, National Panasonic, concluded that the only special feature of MC was that it:

> *"emphasises the use of IT and microprocessor-controlled production machinery, particularly in linking the customer-specification process with the relevant manufacturing process variables required to make the product."*

Quite rightly they pointed out that the combining of pre-engineered modules, which they felt the proponents of MC were saying was essential for the strategy, was just one part of the customization constellation, and was already being explored and carried out in practice.

Others saw MC as meriting closer study and set about understanding the goals and requirements of MC. Davis (1987) did not offer a definition of MC, saying only that customization should be achieved at no greater expense than mass production and one of the notable features of the MC literature is that it lacks a standard definition. Table 2.1 gives the most frequently cited definitions. The majority of authors refer to the definition in Pine's book but other definitions are put forward with Hart (1995) offering two – a visionary and a practical definition (Table 2:1).

Table 2:1 Definitions of Mass Customization

Source	Definition
Pine (1993)	The goal is to develop, produce, market and deliver affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want
Hart (1995)	(Visionary definition) The ability to provide your customers with anything they want profitably, any time they want it, anywhere they want it, any way they want it
	(Practical definition) The use of flexible processes and organizational structures to produce varied and often individually customized products and services at the low cost of a standardized, mass production system
Tu et al (2001)	The ability to quickly design, produce, and deliver products that meet specific customer needs at close to mass-production prices

Enablers of MC have been presented in the literature as being general to all MC contexts and for the most part these have been inferred from a limited set of case studies as pointed out by Da Silveira *et al* (2001):

> *"Literature on MC implementation is still incipient. Most claims are drawn from limited case examples or based on educated guesses from authors rather than from hard evidence obtained through exhaustive research."*

Perhaps a reason for this is that MC has been considered to be difficult and there was an expectation that it would take time before more successes appeared. A second reason has been the focus on consumer goods, as evidenced by the common examples cited in the literature: Levi Strauss jeans (Pine 1993), National Panasonic bicycles (Kotha 1995), Motorola Bandit pagers (Eastwood 1996) and Hewlett-Packard printers (Feitzinger & Lee 1997).

Given the expectation that it would take time for MC enterprises to emerge, the findings of two surveys were startling as both portrayed MC as being a common strategy. Of 40 companies surveyed by Åhlström & Westbrook (1999), 27 considered themselves to be mass customizers. This survey was biased in that only companies that had attended a seminar on MC were approached, but the larger and more general survey conducted by Duray *et al* (2001) gave the same pattern with 126 of 194 respondents being classified as mass customizers. Why the sudden rise in the frequency of MC enterprises? One answer is that these researchers had cast the net more widely. Åhlström & Westbrook (1999) commented:

> *"The survey results indicate that mass customization is not necessarily linked exclusively with consumer goods. Our respondents came from a variety of different industries. Although this is likely to be a reflection of the way in which the sample was chosen, it does indicate that mass customization is not a reality only for companies selling to personal consumers. A majority of companies in our sample sold their products to other businesses."*

A second answer is found in how the researchers tackled *mass*. In both surveys the companies had been asked about *customization* directly, but this was not the case in regard to *mass*. In fact, it is not apparent that Åhlström & Westbrook (1999) attempted to gauge where their companies lay along the mass continuum. This is also true for Duray *et al* (2001). However, they argued that they need only ask about an enterprise's use of modularity as:

> *"modularity can be viewed as the critical aspect for gaining scale or 'mass' in mass customization."*

What is apparent in the literature is that there is agreement that an important goal of MC is to obtain economies of scope (Pine 1993, Tseng & Jiao 1998) that enable customized goods to be as affordable as possible but beyond this agreement two viewpoints of MC have developed. One view is that MC is a label to be given to manufacturing enterprises exhibiting particular structural characteristics, for example as observed in companies that are offering consumers discretion over the attributes of products that have previously been mass marketed to them in standard off-the-shelf configurations. This is the view that Spring & Dalrymple (2000) holds. The other view is that MC is a performance ideal – giving customers the opportunity to have a product *any time they want it, anywhere they want it, any* *way they want it* - in a similar way that *zero defects* is an ideal in respect of quality (Hart 1995). This latter view turns MC into a standard that can be pursued by customizing enterprises in general.

A pragmatic interpretation of MC that blends the two viewpoints is that MC is different from pure customization in that some compromise, limitations or constraints on the degree of customization allowed are inevitable if mass production characteristics - responsive, efficient, high throughput with high quality - are to be achieved and if premium prices are to be avoided. The modularity criteria of Duray *et al* (2000) could be considered to be one such constraint, but it is limitations on the extent of customization that is implied, such as mentioned by Yao & Carlson (2003) who comment that a furniture manufacturer uses recommended fabric combinations as a method of limiting those customizations which could hamper its ability to be lean.

2.1.2 Classifications of Mass Customization

A common theme in the literature is the division of MC into operations sub-strategies. The prevalent way for sub-dividing MC has been by identifying the point along the value chain where customization takes place[6]. An influential work on the subject of customization which is referred to by many researchers is by Lampel & Mintzberg (1996). They divide the value chain into four stages - design, fabrication, assembly and distribution – and define a typology of five strategies that includes *pure standardization*, *segmented standardization*, *customized standardization*, *tailored customization* and *pure customization*. No one type is considered by Lampel & Mintzberg to be *the* mass customization strategy, but a trend toward customized standardization is discerned.

A value chain perspective is implicit in Ross's (1996) five approaches to providing customers on a mass scale with a high degree of choice. Ross doesn't describe the categories but does include example products. At one end of the spectrum is *core mass customization*, an approach in which the customer can modify core elements with Ross giving NBIC bicycles (discussed later) as an example. Then comes *post-product customization* where a customizing service converts a standard product into a customized one (e.g. business software). Below this is *mass retail customization* where customization takes place at the retailer (e.g. spectacles), followed by *self-customizing products* (e.g. PC software, mobile phones), and lastly *high variety push* (e.g. wrist watches). Ross also talks about levels of customization ability, with the lowest being *cosmetic*, which he classes as the easiest type and includes offering a number of colours, surface finishes or materials. A step up in level is *selectable functional options* and the third and highest level is *core customization*. Ross does not cross-link these to the five approaches identified.

Specifically in the context of the automotive industry, Alford *et al* (2000) put forward three distinct strategies of customization - *core, optional* and *form* customization – in which the value chain perspective is also apparent. In c*ore customization* the customer is involved in the vehicle design process such as occurs in low volume specialist vehicles. In *optional customization* the customer is able to choose their vehicle from a very large number of options. In *form customization* customers are able to have limited changes or enhancements made to the actual vehicle which could be dealt with at the dealer or retailer.

Duray *et al* (2000) categorize mass customizers by both the stage along the value chain at which customization appears to take place and the customizing method, which centres on product architecture. The work of Lampel and Mintzberg is drawn on to identify the stage along the value chain and the work of Ulrich & Tung (1991) is used for product architecture. Four categories of mass customizes are named – *Fabricators, Involvers, Modularizers* and *Assemblers*. In terms of the modularity categories, fabricators and involvers can use 'component sharing' or 'cut-to-fit' modularity, while modularizers and assemblers can use 'component swapping', 'mix', 'bus', and/or 'sectional' modularity.

A detailed review of the MC literature, including some mentioned here, is provided by Da Silveira *et al* (2001). They generate eight levels of mass customization ranging from pure customization to pure standardization. Again a value chain perspective underpins their scheme.

A value chain perspective does not underscore the categories of Gilmore & Pine (1997) who introduce four distinct approaches to customization, which they call *collaborative, adaptive, cosmetic*, and *transparent*, with collaborative being the one most often associated with the term mass customization. The underlying dimensions for this scheme are whether the customer is active or passive in prompting the customization and whether the core product is customized or not. The product itself is not changed in adaptive or cosmetic customization.

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[6] Fuller descriptions of five of the six classification schemes noted in this section are given in Appendix B.

2.1.3 Operational requirements for MC

The authors of the early case studies volunteered thoughts on how MC could be made to work in general. For example, to Feitzinger & Lee (1997) there were three organizational-design principles that formed the basic building blocks of an effective MC programme:

> *"1. A product should be designed so it consists of independent modules that can be assembled into different forms of the product easily and inexpensively.*
> *2. Manufacturing processes should be designed so that they, too, consist of independent modules that can be moved or rearranged easily to support different distribution-network designs.*
> *3. The supply network - the positioning of inventory and the location, number, and structure of manufacturing and distribution facilities - should be designed to provide two capabilities. First, it must be able to supply the basic product to the facilities performing the customization in a cost-effective manner. Second, it must have the flexibility and the responsiveness to take individual customers' orders and deliver the finished, customized goods quickly."*

Da Silveira *et al* (2001) observed that interpretations such as the above had influenced others who were interested in MC. They distilled from the literature six perceived requirements of MC:

- Customer demand for variety and customization must exist;
- Market conditions must be appropriate;
- The value chain should be ready;
- Technology must be available;
- Products should be customizable;
- Knowledge must be shared.

Apart from Duray *et al* (2000) none of the other creators of MC categorizations went so far as linking specific operational measures to specific categories. From statistical analysis of survey data, Duray *et al* found correlations between MC strategy and three technologies – design, manufacturing (including process layout and process control method) and administrative. The links are at a high level and are the first observable steps in the MC context towards organisational configurations models (Bozarth & McDermott 1998) as discussed in the first chapter (section 1.2.1)

2.1.4 When to adopt MC and the choice of sub-strategy

Pine (1993) was the first to develop a model to assess whether MC was appropriate for an enterprise. His argument was that MC is a suitable strategy at elevated levels of market turbulence. He used 17 measures to gauge turbulence, under the headings of demand factors and structural factors (Table **2:2**). Each is rated on a scale of 0-100 and the average is interpreted as follows:

- If current market turbulence in an industry is more than 60 points or if the change in turbulence in the past decade has increased by 10 or more points, the industry is undergoing the paradigm shift right now;
- If current turbulence is between 40 and 60 points, or if the level has begun increasing and is expected to continue to do so in the future, the industry is on the threshold of the paradigm shift;
- If current turbulence is below 40 and has not been increasing, mass production remains a viable approach.

Later researchers and commentators on MC have been influenced by Pine and the necessity for market conditions to be appropriate has been a recurring theme. Two subsequent models have emphasised the need for customers to be ready and receptive to customization and they have added that internal factors need to be considered. Both extensions can be seen in the models of Hart (1995) and Da Silveira *et al* (2001) as summarised in Table 2:3, where parallels are drawn between the models.

It is surprising, given the keenness of researchers to provide classifications of MC that none have proposed a decision model to guide an enterprise to one or more MC sub-strategies.

Table 2:2 Market Turbulence factors (Pine, 1993)

Low market turbulence	High market turbulence
Demand factors	
Stable and predictable demand	Unstable and unpredictable demand
Necessities	Luxuries
Easily defined needs / wants	Uncertain needs / wants
Homogenous desires	Heterogeneous demands
Slowly changing needs/wants	Quickly changing needs/wants
Low price consciousness	High price consciousness
Low quality consciousness	High quality consciousness
Low fashion/style consciousness	High fashion/style consciousness
Low levels of pre- and post-sale service	High levels of pre- and post-sale service
Structural factors	
Low buyer power	High buyer power
Independent of economic cycles	Dependent of economic cycles
Low competitive intensity	High competitive intensity
High price competition	High product differentiation
Low to medium levels of saturation	High levels of saturation
Few substitutes	Many substitutes
Long, predictable product life cycles	Short, unpredictable product life cycles
Low rate of technological change	High rate of technological change

Table 2:3 Comparison of two MC adoption models

Hart (1995)	Da Silveira et al (2001)
Customer customization sensitivity	Customer demand for variety and customization must exist
Process amenability	The value chain should be ready Technology must be available Products should be customizable
Competitive environment	Market conditions must be appropriate;
Organizational readiness	Knowledge must be shared.

2.1.5 Categorising product customization

A search through the literature uncovers little imagination in how product customization is described or defined. The literature lacks a concerted attempt to create a terminology of customization. When a customized product is described, the features that are being customized may be listed but the default is almost always to refer to them all as *functions*. An example is the customization of a power transformer in Tseng & Jiao (1998) where they identify the size, total power, safety approval, numbers of outputs, protection, and thermal performance of the product as customizable but lump them all under the heading of functional requirements. In a later paper the same authors say that functional variety is used broadly to mean any differentiation in the attributes related to a product's functionality from which the customer derives a benefit (Jiao & Tseng, 2000).

When customized products are used to illustrate MC, details of the type of customization may be given, such as for Planters peanuts who customized by different package sizes, labels, and shipping containers on an order-by-order basis (Gilmore & Pine 1997). Sometimes only cursory details are given such as in the case of Huffman & Kahn (1998) who say they presented 19 customizable attributes of a sofa to their subjects but they omit to say what these were other than one - 'back shape'. In summary, it is rare for the type of customization to be given much attention and no attempt has been found of creating a generic set of attributes and hence no attempt has been made to consider whether there are relationships between generic categories and operations issues. Given the centrality of the customization concept to Mass Customization, this may be viewed as a significant limitation in the literature.

2.2 Conclusions from the review

2.2.1 Reducing ambiguity in the definition of MC

Although the term Mass Customization has been referred to as an oxymoron (Pine 1993, Hart 1995, Selladurai 2004), on the surface it is a concept that is easy to comprehend. It is in tying it down and in understanding its implications that uncertainties emerge. In the literature there are two types of definition of MC – the *prescriptive* type and the *performance ideal* type. Neither has yet proved wholly satisfactory in the MC context. A weakness of a prescriptive definition is that it creates arbitrary boundaries, while an ideal definition suffers from the opposite problem of conjuring no clear boundaries and allowing many enterprises to be thought of as mass customizers and doing little to explain the differences between mass customizers and plain customizers.

In this research a working definition of MC is used which leans toward the ideal definition of Hart (1995), but creates boundaries by adding a qualification. The working definition is as follows:

> *Mass Customizing enterprises give their customers the opportunity to have a product any time they want it, anywhere they want it, any way they want it and in any volume they want it,along with the benefits associated with mass operations.*

The final statement is the qualification, and it is that to be a mass customizer, an enterprise needs to be attaining the standards of quality, responsiveness and efficiency that are associated with mass production. There are two approaches to testing this criterion. The first is to inspect the enterprise's operations to observe the degree to which it is applying the four principles of mass production[7]:

> *(1) The careful division of the total production operation into specialized tasks compromising relatively simple, highly repetitive motion patterns and minimal handling or positioning of the workpiece.*
> *(2) The simplification and standardization of component parts to permit large production runs of parts that are fitted to other parts without adjustment.*
> *(3) The development and use of specialized machines, materials and processes.*
> *(4) The systematic engineering and planning of the total production process to permit the best balance between human effort and machinery, the most effective division of labour and specialization of skills, and the total integration of the production system to optimize productivity and minimize costs.*

The second approach is to consider the market in which the product competes. If it has competition from mass produced products and it has broadly the same price as these (though economic theory argues it should obtain a higher price, see section 1.1), then it is likely to have achieved the benefits of mass operations.

The working definition, with the qualification that it contains, is unlikely to remove all ambiguity but it does clarify and tighten the domain of this research to initiate the first phase of the study.

2.2.2 Progress towards configurations models

To evoke and explain MC the early protagonists used a few real or imagined examples of MC applications and extrapolated from these some general principles for the implementation of MC. Fledgling steps only have been taken toward configurations models and the question is open as to how to go forward. An option is to accept one of the published MC classification schemes and develop configurations models for each of its sub-categories. The alternative is to reconsider how MC is

[7] Encyclopædia Britannica Online, http://www.britannica.com/

classified and perhaps define a new framework before developing configurations models. Given the concerns raised above, the latter is the preferred route.

2.2.3 Sub-strategy selection

Although MC has been divided into sub-strategies, nowhere in the literature is there a model for guiding the selection of a sub-strategy. The need for such research is highlighted by Brown & Bessant (2003) with the recommendation for:

> *"Developing measuring / positioning frameworks to help strategic decision-makers to identify the particular configuration necessary for their sector or product / market."*

2.2.4 Product customization

There is an absence of a terminology for describing product customization clearly and comprehensively. Being able to categorise how products are customized could allow comparison in terms of the breadth and depth of customization, i.e. is a product being customized a little across many categories or customized in many ways on a few categories? A second benefit could be as a prompt for product development, to aid the creative process and consideration of whether customers would see benefit in each form of customization. Furthermore, the manufacturing and order fulfilment implications of each category could be considered. In other words, a set of generic categories could be used as a bridge between customer needs and process design.

2.3 Research agenda

For the first research goal – advancing understanding of configurations models for MC - the following research agenda and research questions are set out.

- Research agenda 1: appraisal of published MC classification schemes for their suitability as the foundation for operation configurations models, and consideration of alternatives.
  - Q1: do any of the published MC classification schemes provide a starting point for the development of configurations models, or is there a need for a new scheme?
- Research agenda 2: Development of a model for selecting an MC sub-strategy.
  - Q2: can the factors upon which sub-strategy selection is contingent, be identified?
- Research agenda 3: Development of operations configuration models.
  - Q3: can it be demonstrated that sub-strategies require distinct configurations models?

The issue of terminology is identified as a further agenda item.

- Research agenda 4: development of generic terminology for describing product customization.
  - Q4: can product customization be described by a set of generic categories?
  - Q5: are links between specific types of product customization and operations characteristics general or specific?

The research agenda for the second goal of the thesis is expanded on in Chapter 6.

Chapter 3
Methodology for researching MC operational strategies

Abstract

The research method employed in this research facilitates theory building. The process involves observation and analysis of a diverse set of case studies. Primary data is collected from five field studies and supplemented by secondary data from two cases taken from the literature.

3.1 Introduction

The research into MC operations strategies is being approached with the anticipation that general relationships can be identified, and that these will be transferable to other situations in the same domain (or sub-domain). This places the research within the ambit of positivism (Thietart 2001).

The goal is to move towards configurations models. As argued in Chapter 2, there is a question mark over whether any of the MC classification schemes in the literature are a sound first step. To go forward, one approach is to test the classification schemes, for which a *theory testing* methodology should be followed. But the motivation here is to be open to new ways of interpreting MC enterprises, hence a *theory building* method is used, where a theory is viewed as (Remenyi *et al* 1998):

> *A scientifically acceptable general principle or a set of principles offered to explain a phenomenon or group of phenomena*

The intention is, of course, to develop a strong theory, which should constitute: definitions; domain; set of relationships and variables; and specific predictions (Wacker 1998).

Case study research is appropriate for theory building (Eisenhardt 1989, Flynn *et al* 1990, Meredith 1998, Voss *et al* 2002) and is used in the first phase of the research study. The case study approach is accepted as offering advantages for theory construction, notably that the close scrutiny of cases and the richness of information from them encourage the researcher to challenge preconceptions and develop new interpretations (Eisenhardt 1989). The use of case studies in management research has grown (Voss *et al* 2002) and is considered to be an approach that can lead to valid and testable constructs and theories (Eisenhardt 1989, Meredith 1998, Voss *et al* 2002). There are risks in using case-studies for theory building, in particular risks of the theory having a narrow focus, being overly detailed, and there being a lack of transparency in the transition from observations to theory (Eisenhardt 1989).

3.2 Research process

The stages in the theory-building research process are: define the domain; select cases; develop instrument(s); observe and collect data; analyse, develop concepts and construct theory.

3.2.1 Domain

The domain of this research is mass customizing manufacturing enterprises and, as discussed in section 2.2, the working definition of an MC enterprise is one that:

> *gives its customers the opportunity to have a product any time they want it, anywhere they want it, any way they want it and in any volume they want it, along with the benefits associated with mass operations.*

3.2.2 Case selection

The selection of enterprises to study should depend on the research process. For theory building, Eisenhardt (1989) recommends diversity in the cases and that cases that are at the extremes can be beneficial, as opposed to a representative set of cases in a statistical sense that would be desirable for theory testing research. Although a poor set of cases may not hamper the theory building process it can weaken the theory that flows from it.

The seven cases used in this research, of which two are taken from the literature and are hence categorised as secondary cases, are diverse and offer contrasting examples of MC, conforming to the working definition presented. They are summarised below with full details of the five primary case studies in Appendix C. They cover different market segments (consumer electronics, automotive, furniture, leisure), products of different value (from greater than £10,000 to less than £200) products with different lifecycles (from a few months to 3-5 years), enterprises of different scale, size and heritage. It would be untrue to say the case companies had been carefully chosen following a structured screening process. The reality is that management researchers are usually not in the position of selecting cases for study at will and there is an element of fortuitousness in that participating enterprises in this research provided a rich mix.

As well as going into the field the research has made use of cases in the literature. Lewis (1998) argues that reusing case studies can be beneficial and effective in operations management research. Lewis considers the approach brings several advantages such as increasing the breadth and diversity in the material being used for theory building. A benefit of this approach for this research study is that some published cases have been discussed by several researchers, a situation that assists in anchoring the classification schemes. In some instances these researchers have classified these cases according to their frameworks which a) avoids the risk of mis-classifying them on their behalf and b) allows a direct comparison with any new scheme developed.

A question to address is whether these case studies qualify as mass customizers? It is argued that they do. All of these enterprises offer at least some of their customers (that could in some cases be other businesses) the opportunity to have a product any time, anywhere, any way and in any volume they want it. All of them are striving for economies associated with mass production, evident from the design of their products and operations, and confirmed by the fact that all of them are customizing products that compete for market share against mass produced standard products.

Table 3:1 Qualifications as MC enterprises

Name	All or some customers can customise a product?	Mass Production principles	Compete in mass market
NBIC (Bicycle	All	✓	✓
Motorola (Pager)	All	✓	✓
European Bicycle	Some	✓	✓
Computer assembler	All	✓	✓
Commercial vehicle	All	✓	✓
Mobile phone manufacturer	All	✓	✓
Office furniture manufacturer	All	✓	✓

3.2.2.1 Case study summaries

National Bicycle Industrial Company (NBIC)

Kotha (1995) describes how NBIC custom manufactured high-end bicycles with a two week delivery time for the Japanese market, and then expanded it to the international market with a three week delivery time. In 1987 the company set up a second facility next to its mass production plant and introduced a revolutionary production system, named the Panasonic Order System (POS), whereby customers could, by visiting a company dealer, choose from approximately 8 million variants encompassing model type, colour, frame sizes, and other features. By 1992 around 70,000 bicycles were custom made through this facility. The customer was measured in a dealership, where they also selected the model type, colour scheme, and other features. The bicycle dealer completed a form and faxed it to the control room of the custom-made factory. At the factory the details were transferred into the host computer, each order being given a unique bar-code label, which travelled with the bicycle to instruct and control each stage of manufacturing.

The manufacturing resources were developed and built exclusively for use in the custom-factory. To begin the manufacturing process a CAD system generated a blue print of the bicycle's frame and other structural details. Tubing for frame and forks were measured and held by computer-assisted machines for manual cutting. Automatic alignment equipment enabled them to be tack welded and then brazed by automatic brazing machines. The geometry of each frame was checked automatically against its specification using a 3D measuring machine. Overhead conveyors carried the frame and forks to surface cleaning and painting. Preliminary painting by robot preceded finishing by two skilled workers. Before final assembly the customer's name was printed or engraved on the frame or handlebar stem. A bicycle was assembled by a skilled person in one of three stations, taking about 30 minutes. The bicycle was then boxed and sent to holding areas awaiting delivery, from where they were shipped, generally the same day, to dealers to be passed to the customer.

Motorola Bandit pagers

A number of sources (Eastwood 1996, Pine 1993) describe how Motorola began customizing their Bandit pager in the early 1980's, to offer customers up to 29 million product combinations encompassing hardware and software configurations. Production was consolidated in one factory whereas before the project it had been divided between a number of facilities. Customers selected their options and a salesperson entered the specification into a computer system. It is then transmitted to the company systems and on to the assembly process. The facility could accept orders for single pagers in any sequence. The finished product was then shipped to the customer.

Bicycle manufacturer

A European mass manufacturer of bicycles is prepared to customize if expected volumes are sufficient, resulting in customization being limited to large retail customers. It customizes a product for a period of time, not for a fixed volume. Once the product is specified and designed, that customer can order it as if it were a catalogue model – any time and in any volume. Customization requests are not handled through the routine ordering mechanism, but via a customer liaison point. The dialogue is not scripted and the product development process is not fixed. Once the customized product is designed and made available to the customer, it is assigned a product number and the customer places orders in just the same way as for other products. The company does not have separate customization resources. Product development, sourcing, manufacture, warehousing and delivery of customized products are undertaken by the same resources as for catalogue products. Orders for customized products are treated just as those for non-customized products and in this company's case the preferred option is to pick from finished stock rather than manufacture-to-order. Consequently, sales of customized orders are forecast and purchasing and production planned accordingly, as for catalogue models. Other than for graphic transfers that are used as part of the colour scheme, the company does not source new components for a customization. A typical customization involves selecting one of the standard ranges and changing the mix of components and the colour/graphics.

Computer assembler

This company is a computer service provider and mass assembler of computer systems. All computers are assembled-to-order to a configuration selected by the customer. Customers are given considerable choice in the configuration by means of a catalogue that is in the form of a product configurator, and very rarely do customers request configurations outside of this catalogue. Two factors result in a very large variety of products being assembled: the permutations of product configurations enabled by the components on offer and the large diversity in customer requirements. Indeed, approximately 20% of computers assembled have a unique specification. All components are validated before being offered in the catalogue, which includes tests for interactions between components.

Customers place orders via telephone or web and can check on the status of the order at any time, again by telephone or web. The supply and assembly systems are organised so as to cope with the variety on offer. Assembly begins with picking components from stock for a computer and each is assembled as it moves along a bench. All computers then go into a testing and 'burn-in' area where they are taken through a software-driven cycle tailored to their specification before proceeding to packaging and despatch. Although assembly time and duration of tests vary with the configuration no restriction is placed on the sequence of computers through the assembly and test areas since the processes can tolerate the variation.

Mobile phone manufacturer

This company has several manufacturing facilities, supplying mobile phone network operators around the world. Each product is sold to many customers, and is manufactured on a make-to-order basis as far as possible, but any slack time is used to replenish a central warehouse with high demand models.

The product is the mobile handset, the box and its contents which includes manuals and, occasionally, promotional materials. The customizable attributes are: the body of the handset; the flip down front; software of the handset; the antenna; labelling on the body; and the packaging (size of box and contents).

Order size varies from a few (less than 10) to many thousands of handsets. Throughput at this facility is in the order of 6 million handsets per year.

The body colour is determined at the first stage of manufacture, as the body provides structural support to the internal electronics. The handset is assembled by a sequence of robots. A buffer of different coloured semi-finished phones is held at the decoupling point. Up until this point the product is tracked by batch.

To fulfil an order the semi-complete handsets are taken from the buffer to have the appropriate flip cover and antenna attached, software loaded and labels put on. At this point the handset is given its own identity. Finally the box and contents are assembled in readiness for the handset. There is significant variety in packaging and literature for different variants, markets and customers. Apart from software loading all of these tasks are manual.

Flexibility in final assembly operation is needed for customized packaging in particular, as customers have requested their own specification of box as well as literature. On occasion a customer requires promotional items, with an example being a hat, to be inserted.

Commercial vehicle manufacturer

This company is a mass manufacturer of commercial vehicles with several production facilities. The commercial vehicle is designed to be configurable with many options. Each vehicle passing through a plant is assigned to a customer or a dealer and the specification of the vehicle will have been selected by that customer or dealer. Some options, referred to as specials, can involve a part finished vehicle being completed by a sub-contractor. The motivation for creating a new special option is a customization request from a large (fleet) customer. The design is engineered, necessary components sourced and tasks added to the production line. If necessary a sub-contractor is selected and involved at the design stage. Due to the wide range of customizations the development time is variable. Once proven, a special option is added to the catalogue and made available to other customers.

Office furniture manufacturer

The company, with its 120 employees and turnover of £17m, is operating in a competitive market in which there are many drivers for high product variety and customisation, including: corporate image and branding; multi-zoned workplaces; employee welfare; technical demands of specific work environments. The company has 50 product families with 278 base models. Its biggest selling product is a chair designed to allow more than 80,000 combinations of options and on top of this there are over 3,000 standard fabrics in various arrangements. It produces approximately 2,000 units per week and achieves an average lead-time of three weeks.

The company sells to businesses and not to consumers. Customer sales not only cover initial sales, but also include service agreements for replacement of chairs. Sales and service requests are communicated to its telephone sales team at the factory, who take all details assisted by configurator software, and add the order to the production queue. Production involves, fabric cutting, sewing, seat fabrication, assembly and despatch.

Component stock, WIP and finished stock are kept at a minimum, with 56 stock turns per year, two hours of WIP and two despatches per day to customers. The internal production operations are flexible and are reconfigured as the product mix changes. Just over 50% of production is of single products, and almost 80% is for batches of five or less.

3.2.3 Instruments

Two data collection instruments have been used in the research (Appendix A). The purpose of the first instrument was to guide the task of becoming familiar with the activities of a case study company for primary data. At that exploratory stage in the research, insights into processes, products and customers were required, from which theories and models could emerge. As recommended by Remenyi *et al* (1998) a protocol overview was written (presented in Appendix A) that identified the main objectives and issues. A key quotation from the introduction is:

> *'The primary purpose of the familiarisation is to build a repository of observations of contemporary manufacturers, to be used in developing theories and hence principles of mass customisation, along with templates and quantitative models of MC enterprises. With these ends in mind it is without question beneficial to have an appreciation of how manufacturing enterprises produce customised products - how they develop, manufacture and deliver customised products and how they interact with and involve their customers.'*

The first instrument was produced before new concepts or models had been developed and was designed to investigate:

- the customized products and customers of an enterprise;
- the activities of taking and fulfilling orders for customized products;
- the activities around bringing on stream new customized products and new product variants.

The instrument covered many areas which was a benefit in that it protected against prejudice but was demanding to follow. As the research progressed so did the understanding of the breath and depth of information required.

After the modes framework and other concepts had been conceived, a second protocol was developed. Whereas the first protocol was designed to facilitate exploration, this second protocol was focused on the issues and topics that were of prime interest to the research. As stated in the introduction to the second protocol (presented in Appendix A):

> *'The questionnaire allows a profile of an enterprise to be constructed in terms of the mode(s) of mass customization it is currently practicing and an understanding of how its operations are suited and matched to the mode(s).'*

Eisenhardt (1989) addresses the issue of instrument modification and is in favour in the context of theory building research.

3.2.4 Observe and collect data

Three of the five field studies have been studied using the first instrument and one with the second. That this means one company – the mobile phone manufacturer - was assessed without use of either instrument is proof of the pitfalls of field research. Unfortunately this enterprise closed its UK facility only a few months after the initiation of the research. Fortunately, although no protocol had been formalized, over the course of the early fieldwork the production process had been inspected, briefings and data had been given about the operations and support systems of the enterprise, and there had been an intensive Q&A session with representatives of several departments. It is judged the information is of sufficient depth, validity and reliability to enable this case to be used.

In conducting case studies it is recommended that opportunities be taken to use multiple sources and this has been followed in this study (Table 3:2).

Table 3:2 Data collection methods used in the five field studies

Data collection method	i	ii	iii	iv	v
Interviews	✓	✓		✓	✓
Group interviews			✓		
'Walk-through' of activities	✓	✓	✓		
Inspection of facilities	✓	✓	✓	✓	✓
Structured questionnaire					✓
Self-assessment questionnaire				✓	
Review of documentation	✓	✓		✓	
Review of past studies	✓				

i: European Bicycle company
ii: Computer assembler
iii: Mobile phone manufacturer
iv: Commercial vehicle manufacturer
v: Office furniture manufacturer

3.2.5 Analyse and construct theory

The stages in the process of collecting data, analysis and theory development are iterative, as shown in the Figure 3:1. To illustrate the gradual and iterative nature, a context diagram developed early in the research is shown in Figure 3:2. This spider diagram organised factors and variables thought to be relevant to MC that had been identified from observations and literature. The factors have been divided under three main headings – product, order fulfilment, and customers. For the latter two they have been further divided. For each factor the form of a scale is suggested, with and example scale being 'discrete/ modular/ integrated' for *product architecture* (upper right of the diagram). At that time in the research an avenue of study was to categorise enterprises by the status of the variables. Many but not all of the factors in the diagram have been carried forward into the elements of the final theory.

A key stage in the research process has been the development of concepts to underpin the theory. As described in Remenyi *et al* (1998), concept development is a creative step that benefits from data and knowledge of the literature, but can be assisted by drawing on concepts from outside the immediate field of study. In this research the inspiration for the theory of fundamental operations modes came from systems concepts which prompted the development of a process model (Figure 4:1). This departed from the value stream model that was favoured in the literature and whose limitations became apparent as empirical data were collected and analysed. The subsequent re-examination of the case studies from a process perspective led to the development of the theory that MC sub-strategies can better be linked to the characteristics and inter-relationships of processes and activities rather than to stages on the value chain.

Figure 3:1 Research process

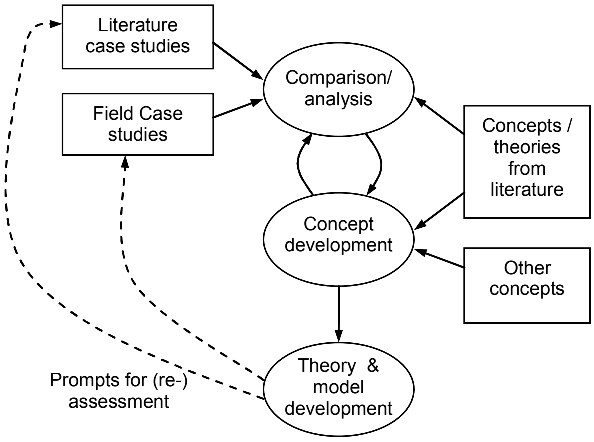
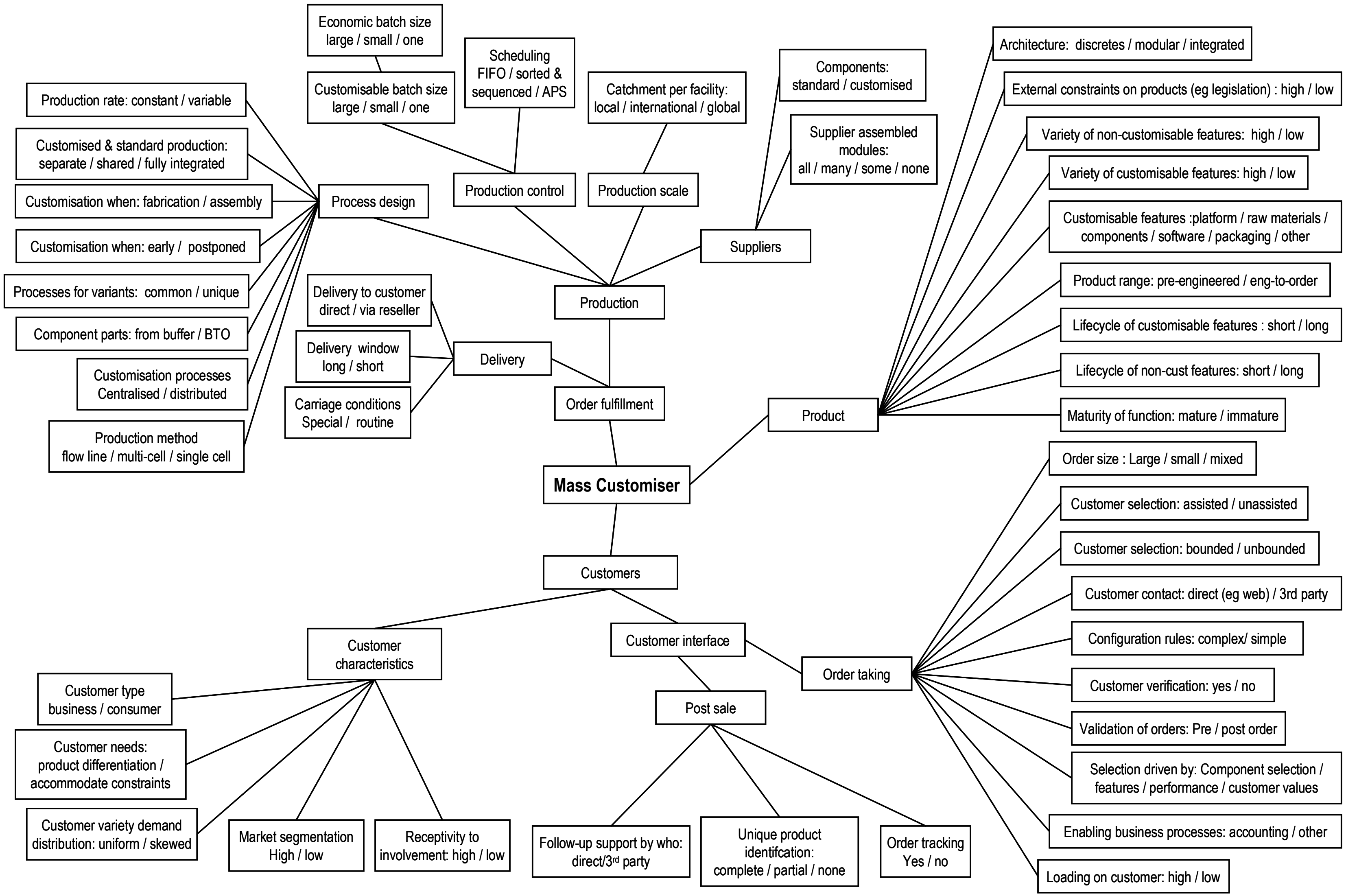


Figure 3:2 An early diagram of the factors in MC operations context referred to as the 'Variables diagram'



Chapter 4
Fundamental MC Operations Modes

Abstract

Six published classification schemes of relevance to Mass Customization are appraised by applying them to the seven case studies. The limitations of the schemes are analysed and their failure to distinguish key characteristics is highlighted. Analysis of the findings leads to the development of a taxonomy of five fundamental operational Modes for MC.

Given that an enterprise has decided to be a mass customizer, the question to address is which Mode or Modes are suitable? A contingent framework is developed for selecting one or more Modes that are appropriate to the enterprises internal operations and its external environment(s).

The information infrastructure required by enterprises to support two of the five Modes is presented to demonstrate the potential for developing organisational configurations models from the modes.

4.1 Application of classification schemes to case studies

To appraise the six classification schemes reviewed in section 2.1.2 (and presented in full in Appendix B), they are applied to the seven case studies introduced in section 3.2.2.1. Table 4:1 summarizes how each case is categorised under each scheme and the assignments are justified below.

Lampel & Mintzberg

By fabrication and painting of the frame, NBIC is practicing *tailored customization.* However a significant aspect of the customization is the selection of components for gears, brakes etc., which accords with *customized standardization.*

The bicycle manufacturer is a mix of *customized standardization* and *tailored customization.* If painting is treated as an assembly task, then, as in *customized standardization,* a special is made from standardized components and assembly is customized while fabrication is not and the product is constructed from a central core. But as in *tailored customization* customers are presented with a prototype (which in this case is a catalogue model) to which modifications are made.

A similar argument can be made for the Office Furniture company and the Mobile Phone manufacturer to be categorised in *customized standardization* and *tailored customization.* In both cases their customers can ask for options not in the catalogue, but with the Office Furniture company it is in the choice of fabric which is straightforward to accommodate and hence this company matches *customized standardization.* At times the customers of the Mobile Phone manufacturer treat the product as a prototype and make requests for new customizations, particularly in respect of software and packaging. This company matches both *customized standardization* and *tailored customization.*

The computer company matches *customized standardization* as all customization takes place at the assembly stage.

The commercial vehicle manufacturer does not fit any category fully but has aspects in common with *tailored customization* and *pure customization.* As with *tailored customization*, the base vehicle is the prototype and customers request modifications, usually in the form of additions, but sometimes they wish parts to be removed. Unlike *tailored customization* there can be significant engineering effort to create the customization. This engineering effort brings it into the realm of *pure customization* and both the customer and manufacturer are involved in decision-making, but the use of the base model prevents it from qualifying as *pure customization* only.

Ross

All of the case studies are judged to qualify as *core customizers*. However, in the case of the commercial vehicle manufacturer, the use of a contractor to complete a part finished or fully finished vehicle taken from the production line also matches *post-production customization*.

Alford et al

Five of the case studies (NBIC, Motorola, Bicycle, Computer and Office furniture) most closely fit the *optional customization* category. For NBIC to be treated as an optional customizer the fabrication of the frame to size needs to be considered in the same way as painting, which Alford *et al* classify as optional customization.

The commercial vehicle company and the mobile phone company can be classified as both *optional* and *core customizers*. In regard to the phone it is the software customizations that qualify as *core customizations* since this involves new coding rather than the choice of optional software functions.

Duray et al

There is some uncertainty in classifying NBIC against Duray's scheme. NBIC's practice of sizing the frame to the customer could be viewed as involving the customer at the fabrication stage, hence they could be classed as a *fabricator*. But this is the category into which customizers of unique designs reside, which overstates NBIC's approach. They could be classified as an *involver* if the frame cutting is thought of as a standard component that has been designed but not cut before the order is taken. They could also be labelled a *modularizer*, since they have applied modular thinking to the product and the frame building task also has a large element of assembly. At this time NBIC are categorised as an *involver*.

The mobile phone can be classified as an *assembler* and as an *involver*. It is the latter when the customers request software or packaging customizations.

The Office Furniture company is similar to the upholsetered furniture company that Duray *et al* use to explain *modularizers*. Like the example company, the Office Furniture company does gain commonality benefits from modularity, but it differs from the example in that modularity is being used primarily to create customer choice, hence it is classified as an *assembler*. The bicycle manufacturer is viewed in the same way and is classified as an *assembler*.

The commercial vehicle company is a *fabricator* and the computer assembler is an *assembler*. The authors cite Motorola as an example of an *assembler*.

Da Silveira et al

Using Da Silveira's scheme the commercial vehicle manufacturer could be said to fit the *additional custom work* category as nearly all special vehicles are standard vehicles that are then adapted. However the extent of design effort per new variant is significant and hence they fit more closely with the *design* category.

In regard to software and packaging customizations the Mobile Phone company fit the *design* category. For other customizations they fit the *assembly* category. NBIC most closely matches the *fabrication* category. Motorola, the computer assembler and bicycle manufacturer fit the *assembly* category. The office furniture company also fits the assembly category but when customers request non-catalogue fabrics they switch to the fabrication category which is defined as the manufacture of custom-tailored products following basic, predetermined designs.

Gilmore & Pine

All case studies fit into the *collaborative customizer* category, which is as expected since Gilmore and Pine refer to this as the approach most often associated with the term mass customization.

Table 4:1 Classification comparison

	NBIC	Motorola	European Bicycle	Computer	Commercial vehicle	Mobile phone	Office furniture
Lampel & Mintzberg	Tailored customization + Customized standardization	Customized standardization	Customized standardization + Tailored customization	Customized standardization	Tailored customization + Pure customization	Customized standardization + Tailored customization	Customized standardization
Ross	Core customization	Core customization	Core customization	Core customization	Core customization + Post-product customization	Core customization	Core customization
Alford et al	Optional	Optional	Optional	Optional	Core + optional	Core + optional	Optional
Duray et al	Involver	Assembler	Assembler	Assembler	Fabricator	Assembler + Involver	Assembler
Da Silveira et al	Fabrication + Assembly	Assembly	Assembly + Fabrication	Assembly	Design	Design + Assembly	Fabrication + Assembly
Gilmore & Pine	Collaborative	Collaborative	Collaborative	Collaborative	Collaborative	Collaborative	Collaborative

4.1.1 Discussion of MC classification schemes

To provide the basis for configuration models, which are models of an organisation and its technologies, a classification scheme should group together enterprises that share similar organisational solutions and keep separate those that have diverse or conflicting needs. In this respect the above schemes have limitations. The schemes do not distinguish or differentiate key characteristics. Three comparisons illustrate these points:

- NBIC, Motorola and the computer company all make unique products to-order in lot sizes of one. In all cases manufacturing is triggered by a customer's order, and apart from the frame in the case of NBIC, all components are off-the-shelf. Consequently they can be expected to share characteristics, but in only three of the six classification schemes are they placed in the same classification. In the other three schemes, only Motorola and the computer company are placed in the same classification.
- The European bicycle company and the commercial vehicle manufacturer both apply a policy of customizing in anticipation of repeat orders and both give customers considerable leeway in when and in what quantity customers can re-order products. In addition both create customized products by adapting existing variants in the catalogue, and both consequently need to ensure that customized designs remain producible as changes are made to catalogue products. Although in other respects these companies differ, in particular in how they organize manufacturing and assembly, and acknowledging the design effort per customized vehicle can be considerably greater than per bicycle, nevertheless it is likely they could benefit from similar organizational solutions for the tasks they have in common. While there is overlap in the classification of these two companies against some of the schemes, the overlap is due to ambiguities in the interpretation of the extent of customization rather than due to organizational similarities.
- The European bicycle company has approached customization in a different way to NBIC, to an extent where the technologies it can use to achieve high performance are different from those NBIC has employed. However, in all but one scheme – Duray *et al* - they are assigned the same classification. If the European bicycle company shifted to customizing orders for single bicycles rather than in bulk as it does at present, it would be expected that it could learn much from NBIC. Even when moving to one-at-time customization it would remain an *assembler* in Duray's scheme while NBIC is an *involver*.

Of the six classification schemes, Gilmore and Pine's is the most straightforward to apply. There is a degree of uncertainty in assigning the cases with the other five schemes. The ease of applying Gilmore and Pine's scheme is partly due to it not taking a strongly value chain perspective. However, its focus is wider than mass customization manufacturing and consequently, as found here, enterprises with notable differences are grouped together. The scheme is not therefore a strong candidate as the starting point for configuration development.

It is useful to analyse the value chain perspective further. The uncertainties in applying the approaches that adopt a value chain perspective stem from the premise used implicitly in these schemes that there is a *single point of customization*. Reality is different. A product can have some features that involve customized fabrication and other features that entail customized assembly. Take as an example a customized bicycle from NBIC. While the frame is the largest item, a typical model has approximately a hundred other component types (i.e. counting spokes as one component type or a rear Derailleur gear set as another component type). The selection of these components is a significant part of customizing a bicycle, but unlike the frame and forks, NBIC will not fabricate them.

Detailed analysis and application of the published schemes has highlighted reasons for the limitations. The weaknesses of the value chain classifications are that it under-emphasises two key distinguishing factors in how enterprises provide customized products and omits a third factor. The two factors given insufficient prominence or consideration are:

- *temporal relationships between activities*, in particular between design and validation activities and other order fulfilment activities; and
- whether the technological *resources* used in order fulfilment are *fixed or modifiable.*

The third factor, omitted in the schemes, is the *repetition of customizations*.

4.1.1.1 Temporal relationships between activities

The first factor – *temporal relationships between activities* - is not explicit but is detectable in all of the value chain based classifications, since all have at one extreme a category in which considerable design effort occurs per customer, and at the other extreme a category in which design is fully complete before the first purchase. The temporal relationship between activities such as design, fabrication and assembly is a common way of differentiating non make-to-stock manufacturers, using categories such as assemble-to-order, make-to-order and engineer-to-order (Slack *et al* 1998, Amaro *et al* 1999). From the case studies there are three temporal relationships to be accounted for.

- Firstly there is design and validation *per product family* where these processes are completed *before* any customer places an order for a product.
- Secondly there is the *per order* situation when the customer is involved during each order fulfilment cycle, i.e. the customer's product is designed and engineered between order taking and delivery.
- Thirdly there is the *per product* relationship where design and validation take place at the prompting of the customer but prior to (repeat) orders being placed by the customer for that product.

4.1.1.2 Fixed or modifiable order fulfilment resources

The second factor – *fixed* or *modifiable order fulfilment resources* - is implicit in the schemes but almost hidden. It is most visible in the scheme of Da Silveira *et al* who include the category 'additional custom work' but this scheme does not carry the idea to its logical conclusion, which is that customizers either restrict the extent of customization to that which they can fulfil within the envelope of their present fulfilment resources (encompassing *materials supply, processing* and *delivery resources*) or they modify them, such as by investing in additional or different process technology or engaging a new supplier or subcontractor to enable the manufacture of the customized product.

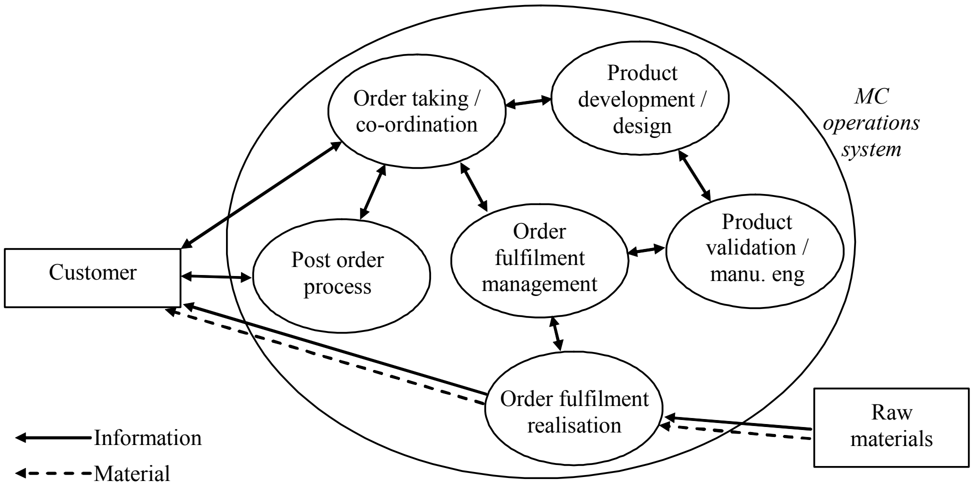
4.1.1.3 Repetition of customizations

The factor which the classification schemes have omitted is whether an enterprise is prepared to customize a product on a *once-only* basis or whether they customize only on a *call-off* basis, in which they accept a customization commission if repeat orders are likely. The latter is similar to 'Repeat Business Customizers' identified by Amaro *et al* (1999). The call-off approach is typical, for example, for suppliers to the so-called 'mass merchants' (McDermott & O'Connor 1995) whose desire for product differentiation influences their buying decisions and leads them to make requests for customized orders, customized lot sizes, customized packaging, and customized shipping schedules. For example, they dictate when and how a promotion is run and the type of promotion specials required, such as an additional spare part or a gift item in a package.

4.2 Identification of MC operations Modes

Having identified these three important distinguishing factors, they are used now in the identification and development of fundamental operations Modes for Mass Customization. The primary Modes have been identified by linking the distinguishing factors discussed above to a generic MC operations process model, shown in Figure 4:1.

Figure 4:1 Core operations processes



4.2.1 Core Process model

The core process model is a representation of the operational activities involved in fulfilling a customer with an order. There are six processes within the MC operations system, and the links between them represent information and material flows. External to the system are *Raw materials* and the *Customer*. Raw materials (or components) feed into the system and the finished product is delivered to the customer. The six processes are:

- *Order taking / co-ordination*: this process manages the dialogue with the customer, receiving and interpreting the customers' wishes, coding them for verification by the customer, finding a product solution for the customer and generating the details of the order.
- *Product development and design*: this process handles the design for the customer. Compliance with external and internal standards is within its scope.
- *Product validation and manufacturing engineering*: this process is responsible for confirming the manufacturability of the design and its translation into a set of manufacturing procedures and rules. It will typically generate the bill of materials for the customized products and provide guidelines on routing and processing instructions.
- *Order fulfilment management*: this process manages the order fulfilment value adding chain, including the supply chain. It interacts with the order co-ordination process, informing it of when it can complete an order and schedules and controls the order fulfilment activities.
- *Order fulfilment realisation*: this process encompasses the activities executed in the manufacture of products, and includes supplier activities, internal manufacturing processes and delivery activities.
- *Post order process*: these are activities that (may) follow the completion of an order, such as maintenance, warranty claims, technical guidance, etc.

4.2.2 Fundamental Modes for MC

The process model enables the three distinguishing factors to be operationalised and linked to the core processes:

- The first factor – temporal relationships – dictates when the processes are executed relative to each other. The *product design* and *product validation* processes can be executed *per product family*, *per product* or *per order*[8].
- The second factor – fixed or modifiable resources – is mapped onto the *order fulfilment realisation process*.

[8] *per order* – activities are performed every time an order is processed
per product – activities are performed once, when the product is created
per product family – activities are performed once, when the product family is created

- The third factor - whether an enterprise customizes a product on a *once-only* basis or on a *call-off* basis - has a bearing on temporal relationships (i.e. *product design* and *validation* are performed only at the inception of a customized product) and on how the processes are implemented, such as the control methods used by *order fulfilment management*.

In total there are twelve possible arrangements - three temporal states, two resource states and two repetition states. Each is a 'Mode', which is a *particular functioning arrangement*[9] of the process model. However, not all twelve are feasible. For example, when the product range is designed prior to orders being taken (*per product family*), it is assumed the order fulfilment resources are *fixed* and there is no difference between a *one-off* and a repeat *call-off* order. From this analysis, five fundamental modes of operation for MC can be identified. These are shown diagrammatically in Figure 4:2. They are named and described below and summarised in Table 4:2:

Mode A: Catalogue MC

Customers select from a pre-specified range and the products are manufactured by the order fulfilment activities that are in place. Likewise the order fulfilment activities are engineered ahead of an order being taken. In this Mode the design and engineering of products is not linked to orders, but completed before orders are received (i.e. on a *per product family* basis).

Mode B: Fixed resource design-per-order MC

A customer order is fulfilled by engineering a customer specific product, produced through standard order fulfilment processes. The customer places one order for the product and there is no expectation of repeat orders. In this Mode there is some degree of product engineering for each order (i.e. *per order* basis), unless a customer's wishes happen to match a previous order in which case the product design is reused. Because the order fulfilment process is standard all designs must be suitable for the process. Therefore it is important that the product development process is aware of the process capabilities.

Mode C: Flexible resource design-per-order MC

A customer order is fulfilled by engineering a customer specific product, and produced through modified order fulfilment processes. The customer places one order for the product and there is no expectation of repeat orders. In this Mode products are engineered per order and the order fulfilment process may be modified per order.

Mode D: Fixed resource call-off MC

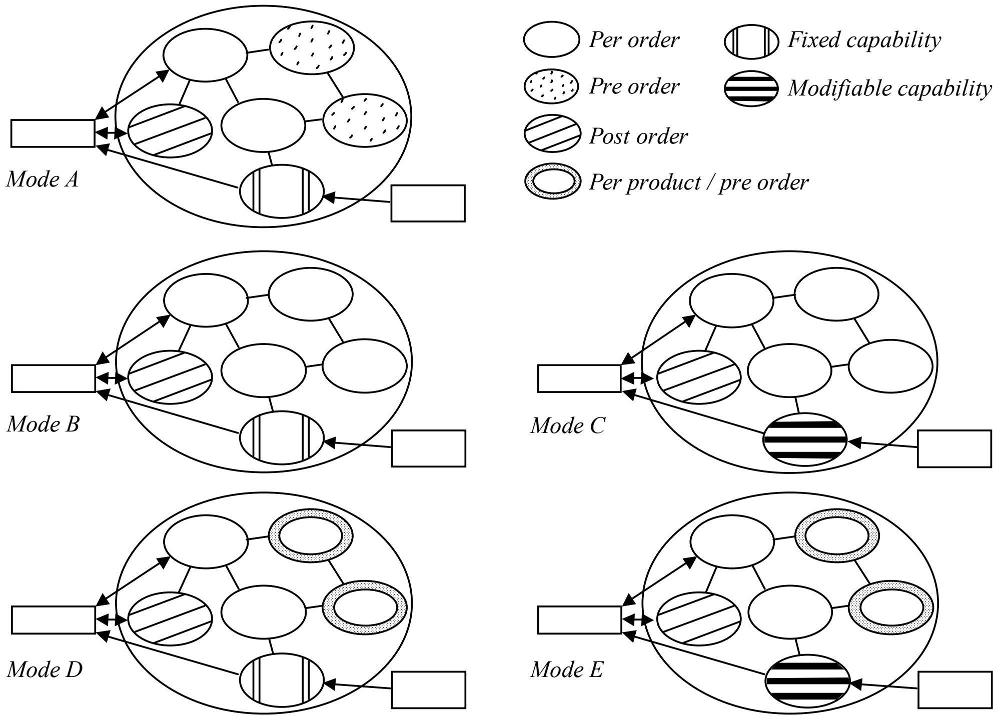
A customized product is designed for a customer, to be manufactured via standard order fulfilment processes in anticipation of repeat orders. At the prompting of a customer a product is designed and engineered that can be manufactured through the standard order fulfilment process, and the customer can re-order the product at any time.

Mode E: Flexible resource call-off MC

This Mode is the same as Mode D except that the order fulfilment activities are modifiable. A customer order is fulfilled by designing and engineering a customer specific product, and produced through modified order fulfilment processes. There is an expectation of repeat orders.

[9] Definition of *Mode* from Merriam-Webster Online Dictionary, http://www.m-w.com/cgi-bin/dictionary?book=Dictionary&va=mode

Figure 4:2 The Five Fundamental MC Modes



4.2.3 Classifying the case studies by Mode

Six of the case studies comply with the requirements of Catalogue MC (Mode A) as listed in Table 4:2 and for four companies this is the only category they fit. The office furniture, computer assembler, Motorola pager and NBIC all design and engineer their product range prior to accepting orders, hence they operate on a *per family* basis. Their order fulfilment resources are matched to the product range, hence they are *fixed* and they treat one-off and repeat orders alike.

For some customers the bicycle manufacturer, commercial vehicle manufacturer and mobile phone manufacture engineer a customized product on a product *'by product'* basis, ahead of it being manufactured. They take on a customized product in anticipation of repeat orders. They differ in whether they modify their order fulfilment resources for a customized product. The phone manufacturer and bicycle manufacturer constrain their customers to the capabilities of their existing component range and manufacturing activities (Mode D), whereas the commercial vehicle manufacturer is prepared to modify and extend its order fulfilment resources by taking on new suppliers / contractors or altering / adding processes that are performed in-house or by existing contractors (Mode E).

4.3 Discussion of the Modes

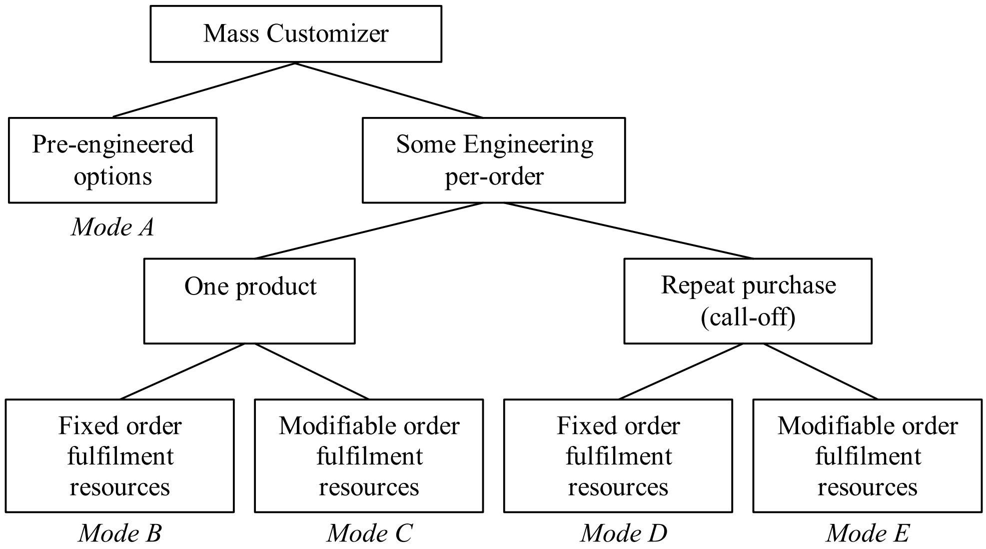
These Modes add to the knowledge on the 'content' of mass customization – what MC is and what the activities within MC are.

It is expected that a mass customizing enterprise will comply with at least one of the modes. However, a company can operate in more than one mode, even in regard to the same product family. For example, the commercial vehicle manufacture has one product family but it operates in Mode E (Flexible resource call-off MC) for a proportion of its customers and for the remaining customers it operates in Mode A (catalogue MC) hence this enterprise is listed under both Modes in Table 4:2. Some parts of its organisation are involved solely in Mode E. This demonstrates the feasibility of multi-modal operations.

Any classification is necessarily an approximation of reality, balancing the level of detail necessary to capture important characteristics against the need for a tractable scheme that is not overly complex. It depends also on where the boundaries of the domain are set. For instance, contract manufacturing has not been considered in the Modes scheme. As the Modes are further researched the applicability of the concepts to the contract manufacturing business model can be explored. It is possible that when contract manufacturing is considered the taxonomy may need to be extended.

A feature of the Modes is the commonality between them. Some organisational characteristics can be expected to be beneficial to several modes. For example, enterprises that conform to Mode D or E engineer a product with customer involvement and then manufacture that product as and when necessary. Mode E enterprises have the added challenge of scoping and implementing modifications to their order fulfilment resources and therefore their organisation will differ from Mode D companies. However Mode D and E companies can be expected to share some organisational characteristics and technologies that are relevant to their common practices. Therefore, although the Mode classification assigns the Mobile phone and European bicycle manufacturers to one and the commercial vehicle manufacturers to the other, the Modes scheme expects technologies that are beneficial to one to be beneficial to the others. A tree-diagram of the Modes reinforces the notion of commonalities between Modes (Figure 4:3).

Figure 4:3 Mass Customization Modes of operation



The five Modes can be interpreted from the two emergent viewpoints of mass customization discussed in Chapter 2. The first is that to be a mass customizer an enterprise should exhibit characteristics such as having a pre-engineered product range and an order fulfilment system ready and capable of manufacturing and delivering any variant in the range. Mode A encapsulates this viewpoint. The second is that MC is a performance ideal, in which the goal is to fulfil each customer with any product, any time, anywhere, any way they want it, regardless of what product the previous or the next customer receives. Modes B and C can be interpreted as being operational Modes geared to this ideal. The last two Modes (D and E) blend the two viewpoints and they reflect the richness of reality in which customers demand customization but the diversity of their needs precludes pre-determining product options.

Table 4:2 Mode summary

	A **Catalogue**	B **Fixed resource design-per-order MC**	C **Flexible resource design-per-order MC**	D **Fixed resource call-off MC**	E **Flexible resource call-off MC**
Temporal relationship - Product design	Per family	Per order	Per order	Per product	Per product
Product validation / manu eng	Per family	Per order	Per order	Per product	Per product
Once-off / Call-off	-	O	O	C	C
Fixed / Modifiable order fulfilment resources	F	F	M	F	M
Classification of case studies	NBIC, Motorola, Computer, Commercial vehicle, Mobile Phone, Office Furniture			European Bicycle, Mobile Phone	Commercial vehicle

4.4 Mode selection framework

The role of a Mode selection framework is to link an enterprise to a mode. It is not an objective of the framework to assess whether an enterprise should or should not become an MC enterprise or whether it is ready for MC. The starting point is that the enterprise is already a mass customizer or has decided to become one. Consequently, the framework is not an alternative to those of Pine (1993) and others that are summarised in Chapter 2, section 2.1.4. It does have factors in common with earlier frameworks and this commonality is discussed.

The framework has been developed from an understanding of the Mode classification and from observations of the case study companies. It uses four factors to evaluate the fit between an enterprise and a Mode (Table 4:3). Two of these factors are concerned with the *business environment* and two with *internal factors* of the enterprise.

Table 4:3 Mode selection factors

Factor	Description
(i) Customer power	The more powerful the customer the greater the pressure they can exert to reduce their compromise in a purchase and demand a customization that meets their needs more precisely than pre-engineered options in a catalogue.
(ii) The strength of customer desire for differentiation from other customers	Retailers/Resellers are an example of customers that value differentiation. They seek to offer unique advantages to their customers and one approach is to offer distinctive and unique versions of products, or to promote the product in a unique manner. Consequently, to get unique products they can push customizers to go beyond the boundaries of their standard catalogue options.
(iii) Cost of engineering and mobilising an additional option	Costs can be incurred in engineering a new variant or in readying additional fulfilment resources, such as finding new suppliers or acquiring new equipment or skills.
(iv) Implications of a new variant on order realisation	If further variants of a product are, in effect, unique permutations of a standard set of components, a new variant may have little impact on sourcing arrangements, costs, quality and lead time. New customizations could create problems, e.g. the mix of products creates difficulties for planning and scheduling, due to changeover requirements and unbalancing the process, or in respect of inventory and WIP costs.

The preferred MC operations Mode for an enterprise will be influenced by the status of the four factors:

- *If factor (i) or (ii) are rated as high, the enterprise should not follow Mode A (Catalogue MC).* Across all of the Modes, it is in Mode A that an enterprise has the highest degree of self determination over the customization it offers. Customer power or a need among customers for product differentiation reduces the level of control and increases uncertainty over what customers will be seeking.
- *If factor (iii) is rated as high, the enterprise should not follow Modes B or C.* These two Modes involve customization on a once-off basis, but a high cost of introducing a new customization may threaten the economics of these Modes. Either Mode D or E, in which the enterprise can spread the cost over repeat sales, are likely to be better fits for such an enterprise.
- *If factor (iv) is rated as high, the enterprise should not follow Modes B or D.* These two Modes involve customization without modifying the order fulfilment realisation resources. An enterprise can operate in these Modes if new customizations have little bearing on the resources. But if it is difficult for the enterprise to perform customization using their existing resources they should be operating in Mode C or E.

4.4.1 Applying the selection conditions to the case studies

The bicycle company was attempting to follow Mode D in which it accepted call-off customizations from its powerful buyers and fulfilled them without modifying its fulfilment resources. However, it is given a *high* rating for factor (iv) due to the low responsiveness of suppliers (Table 4:4). In the framework a high rating for this factor is incompatible with Mode D. Indeed the company was finding it difficult to follow this Mode and had to increase its inventory in order to cope with new customizations.

The circumstances of the commercial vehicle manufacturer were such that it was unwise for it to restrict itself to Mode A. Many of its customers were small or medium businesses and these customers were channelled through Mode A. However, the customization of vehicles for large fleet customers, such as recovery services or utility companies, was a significant proportion of its business. The customizations were not the sort that could be foreseen nor were many of them reusable for other customers. These customers were more concerned with having vehicles that were customized to meet their functional needs than with the vehicles being different from other customers (though a unique livery was usually important). It was common for the first special vehicle to be treated as a prototype with improvements to the specification established through user trials. To attempt to predict the specific need of these customers would risk wasting considerable engineering and process development costs. For these customers the company followed Mode E and this fits with the selection framework due to the *high* rating of factor (iv).

For the mobile phone manufacturer factors (i) and (ii) are rated as *high*. Their customers were global network operators with buying power and a wish to differentiate themselves from their competitors. The company was continually introducing new customizations at their behest which involved customization of the product and of its packaging, including the insertion of promotional items in the package. Even though the mobile phone manufacturer rated *low* for factors (iii) and (iv) they at no time operated in Modes B and C as might be expected from the framework. They themselves judged their systems were capable of handling one-off orders, but due to the size of their customers this situation did not arise and they operated in Modes A and D.

The computer assembler and the furniture company operated as catalogue mass customizers (Mode A) and the ratings of factors (i) and (ii) were low for both enterprises. Both had a large number of customers, among whom it was not a priority to differentiate their products from other customers. Both companies only very rarely received requests for specials outside the extensive options /variants available that would require additional engineering or sourcing alternative components and in most cases these were declined. This means that they comply with the Modes selection framework. It is worth noting that for factors (iii) and (iv) these enterprises have opposite ratings. It is judged that the implications of a new variant to the computer assembler is *low* for both the engineering and order realisation processes, whereas for the furniture company the impact can be *high* for both. This observation supports the supposition of the Mode selection framework that it is the status of factors (i) and (ii) that determine whether Catalogue MC (Mode A) is viable.

4.4.2 Discussion of the Mode selection framework

The framework is presented as a selection framework, but a more accurate description would be that it is a de-selection framework as the conditions look to rule-out modes.

The selection framework, with internal and external factors, is similar in style to the models proposed for assessing the suitability of MC for an enterprise (see Chapter 2) but the factors have a narrower focus. For example, Pine's (1993) model includes the factor *Buyer Power*, which combines the issues that have been split into factors (iii) and (iv) in the selection framework. Of Buyer power Pine writes:

> *"[i]t ... results in more variety and customization as firms differentiate their products – especially when buyers value variety at least as much as price."*

For an enterprise, the grading of the factors could change over time, particularly the external factors and could force a customizer to adopt a different Mode. A shift in a factor's grading can be enforced on a customizer or self determined, as illustrated by the commercial vehicle manufacturer who chose to take on aftermarket customizers and as a consequence could not follow Mode A alone but had to adopt Mode C or E and chose the latter because of the cost of engineering and mobilising for a new customization prohibited accepting once-off orders.

Table 4:4 Mode of operation of each case study enterprise and ratings of Mode selection model factors

	Bicycle	Computer assembler	Mobile phone	Commercial vehicle	Furniture company
Mode					
Mode A: Catalogue MC		✓	✓	✓	✓
Mode B: Fixed resource design-per-order MC					
Mode C: Flexible resource design-per-order MC					
Mode D: Fixed resource call-off MC	✓		✓		
Mode E: Flexible resource call-off MC				✓	
Factor					
i) Customer power	High	Low	High	High	Low
ii) Customers need differentiation from other customers	High	Low	High	Low	Low
iii) Cost of engineering / mobilising an additional option / variant	Low	Low	Low	High	High
iv) Implications of a new option / variant on ingredients or process (raw materials or components)	High	Low	Low	High	High

An implication of this framework is that no single Mode should be treated as the ultimate or ideal Mass Customization Mode. The tendency in the literature is to assume catalogue MC (i.e. Mode A) is the only legitimate form of MC. However, according to this selection framework, this Mode is not viable if external factors are against it.

In Mode A customers select from a catalogue of pre-engineered options but it is a Mode that would be difficult to implement by enterprises who supply *mass merchants*, as pointed out by McDermott and O'Connor (1995). Mass merchants are powerful and make requests for customized orders, customized lot sizes, customized packaging, and customized shipping schedules. Mass merchants dictate when and how a promotion is run and the features of the promotion which could be a special version of the product, an additional spare part or a gift item in a package. Mass merchants are keen to differentiate themselves from other sales channels and one approach is to stock products not available elsewhere. Consequently mass merchants can frequently push suppliers to go beyond their catalogue significantly. For these enterprises Mode D or E is preferable and attempting to operate in Mode A would lead to conflict and inefficiencies. In the case of the commercial vehicle manufacturer, even though its customers are not mass merchants and so do not seek differentiation for differentiation sake, it is unlikely to switch from Mode E. Its customers' needs are too diverse to be predicted and the cost of developing product variants does not make it worthwhile to attempt to anticipate its customers' needs.

It has been observed that enterprises operate in more than one Mode. These enterprises segment their customers and in this situation the selection framework can be applied to each segment.

The selection framework has identified one case study company as operating in an inappropriate Mode – the bicycle manufacturer. Since its involvement with this research this company has closed its UK facility. It is not suggested here that the inability of the company to change its MC Mode was the prime cause of the closure, but it is symptomatic of the company's general difficulties to adapt its operations to changing market conditions.

4.4.3 Future development of the Mode selection framework

By creating rating scales and a scoring method for each factor, along with interpretation criteria, the framework could be converted into a decision support tool.

4.5 Developing configuration models from the Modes

For the Modes framework to be the foundation of configurations models there needs to be dependencies between the Modes and organisational characteristics such as: organisational structure, information and data processing, quality assurance and control, product design and validation technologies, order fulfilment approaches. To illustrate the potential for taking forward the Modes, the core process model (Figure 4:1) is developed into information infrastructure models for two modes. The models are informed by field observation but are conjectures as they have not been validated.

4.5.1 Information infrastructures of two Modes

Differences in the information requirements of each Mode reveal themselves in terms of the types of information stores used, the communication links between the six core processes and the information transformations within the six processes. The first two of these are made explicit by a process diagram in the form of Data Flow Diagrams[10] in Figure 4:4 and Figure 4:5, the former for Mode A (Catalogue MC) and latter for Mode B (Fixed resource design-per-order MC).

Some of the links and stores are common to both Modes (and may be common to other modes) and in many instances the links and stores have the same role, but for some they are different. For example, in the upper left of each diagram a customer expresses their wishes to the order co-ordination process which in turn codes their wishes for the purpose of customer verification (marked as item 1). The customer's coded wishes are communicated to the product design process but, whereas in Mode B this is to facilitate designing a product for that customer, in Mode A the link is for the purpose of providing market intelligence to the design function (because in Mode A customers are selecting from a pre-designed catalogue of products, but any opinions or comments they have about them may be useful for the development of future products).

Differences between the Modes are most obvious on the right side of each diagram. In Mode A the product design and product validation processes build and maintain 'live' catalogues of designs and product recipes respectively (items 2 and 3). The product design catalogue is searched by the order taking process on behalf of each customer as is the catalogue of product recipes by the order fulfilment management process. In Mode B the product design process generates a product design for each customer (represented by data store 5) and the product validation process generates a recipe for that product (represented by data store 6). The 'live' design and recipe catalogues that are in Mode A (items 2 and 3) are not present in Mode B, but both Modes keep libraries of past designs and recipes (items 7 and 8).

In Mode A short term unavailability in the order fulfilment system can mean some catalogue items are unavailable. Consequently, in this Mode the order fulfilment management produces a status report on availabilities, which is linked to the product catalogue (item 4) to enable product options to be temporarily removed. The availability information is handled differently in Mode B. In this Mode the availability information (item 9) is fed into the product validation and manufacturing engineering process which has the task of ensuring products can be produced. This process will advise the product design process if a lack of availability has implications for a design that is being produced for a current customer (item 10).

[10] A brief description of Data Flow Diagramming is given in Appendix D

Figure 4:4 Information Infrastructure for Mode A (Catalogue MC) (Note: the core processes are shaded using the notation from Figure 4:2)

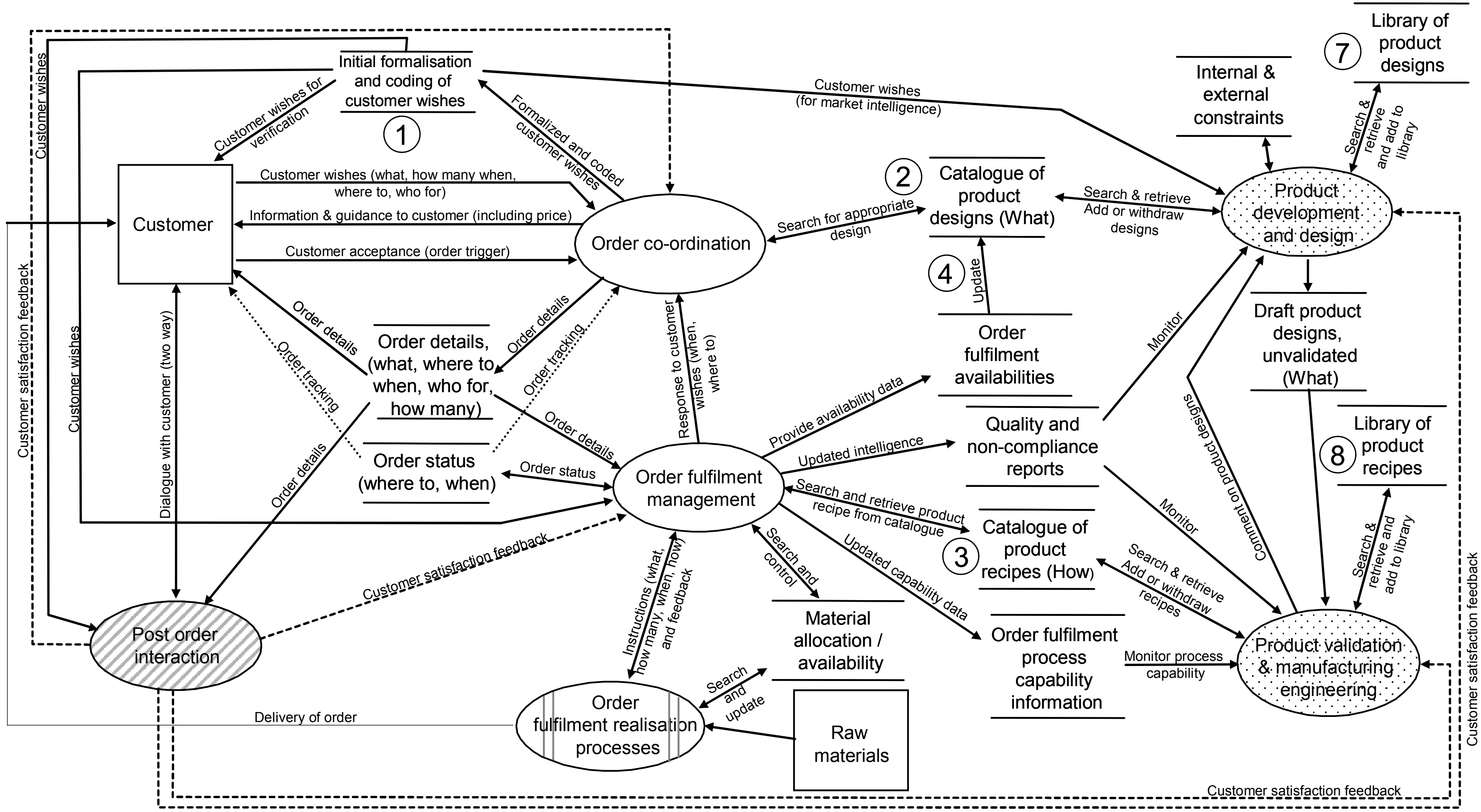
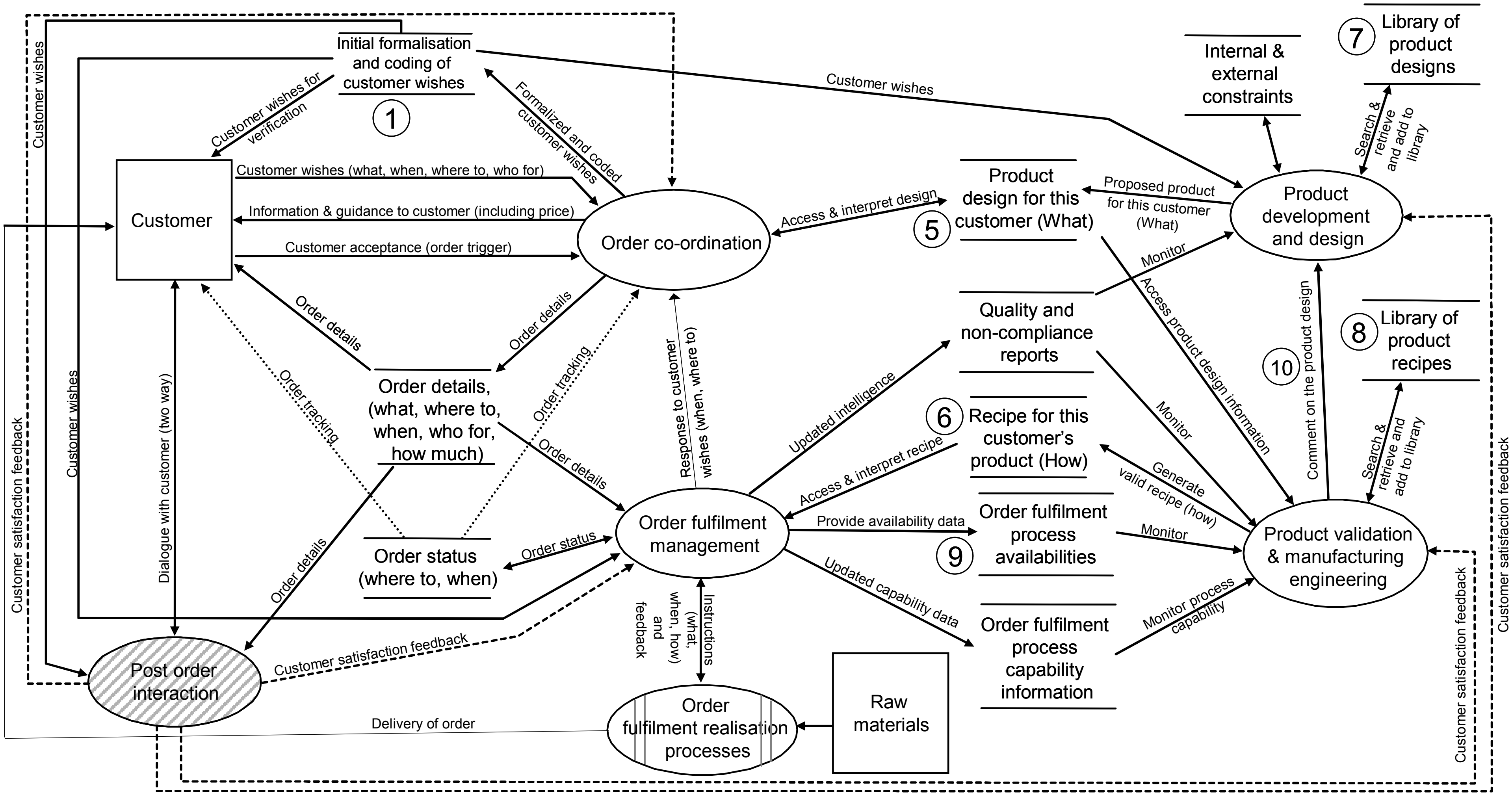


Figure 4:5 Information Infrastructure for Mode B (Fixed Resource, Design-per-order MC) (Note: core processes are shaded as in Figure 4:2)



4.5.2 Information infrastructure inhibitors and enablers

The models of information infrastructure are design templates and can be used in the testing and verification of an enterprise's systems. Each process, link and data store in the information model can be analysed in the same manner:

- Does the process / information link / data store exist?
- Does it have / would it have limitations as the enterprise moves toward mass customization? Are the anticipated limitations due to more mass characteristics or limitations due to more customization?

At least five constraints could occur?:

- *Customization flexibility*: e.g. the link/ process/ store cannot transmit/ transform/ store customization details per order;
- *Speed*: e.g. the speed of the link/ process is too slow to cope with customization per order;
- *Volume*: e.g. the link/ process/ store cannot process/ store the necessary throughput/ number of customized orders;
- *Cost*: the cost of the link/ process/ store would become excessive as customization increased;
- *Quality*; as customization increases the link/ process/ store is prone to quality problems.

4.5.3 Observations from the case studies

Observations from the case studies, including from a workshop at which the inhibitors/enablers review method was trialled indicate that information systems have a bearing on MC performance and that the information infrastructure of the Modes are different. Notable observations are:

- The information systems of the European Bicycle company were designed for mass production. Customer enquiries for customizations could not be handled through the normal order taking process. The information system had no flexibility and the only method of identifying a product was with a product code. The system of the Office Furniture company provided a contrast. This company had recently installed a configurator, one function of which was to support order taking. The data-fields and interface facilitated the task and free-text fields could be used to record additional information.
- Although the Office Furniture company had acquired new information systems, it did not have the ability to check component availabilities at the time of order taking and hence there was a risk that promised delivery dates could not be met. The systems of the Computer Assembler enabled it to check availabilities immediately and customers would be advised of shortages at the time of order entry;
- The systems of the Computer Assembler automatically monitored and resequenced the queue of production orders for the purpose of ensuring orders would be despatched within promised lead times;
- The Commercial Vehicle Manufacturer had difficulty in devising an information system that could handle both Mode A and Mode D. Having engineered a new call-off customization for a customer (in Mode D) it had difficulties in transferring it into the standard catalogue and hence the standard material planning and production control systems.

Chapter 5
Customizable attributes

Abstract

A set of generic customizable attributes is developed to provide the mass customization community with a terminology for product customization. Observations are made on the nature of linkages between customizable attributes and process operations. An approach for identifying which customizable attributes a producer should prioritise is developed in concept. The approach is to measure differences across customers in their perceptions of product configurations and derive from this the attributes that should and should not be customized.

5.1 Introduction

It is routine to describe products from multiple perspectives - the manner in which customers describe a product seldom bears relation to how it is described for manufacturing. As no single language can suffice, conversion from one viewpoint to another is necessary. In Quality Function Deployment a product is described and mapped between the perspectives of customer needs, components and process factors (e.g. Fung *et al* 1998). Mappings between viewpoints is part of the methodology for MC product design by Jiao and Tseng (2000) which uses three views - functional features (FFs), technical parameters (TPs), and component/ assemblies (CAs). Neither in QFD or the Jiao and Tseng method are standard sets of descriptive terms put forward for any of the perspectives. The aim in this chapter is to develop the terminology for describing product customization. In the field of product design there is a relevant precedent for doing so in the form of a set of modularity types by Ulrich and Tung (1991).

An argument against a generic set of customizable attributes[11] is that they would be too general and too 'coarse grained' to assist the product design process, and that links between customer needs and process factors are likely to be product/process specific and therefore be independent of attribute. The aim here is to examine how products are being customized and synthesise a generic set of customizable attributes. The potential for using them to understand the links between customer needs and the manufacturing and fulfilment process is considered.

5.1.1 Scope of the set of customizable attributes

The objective is to specify a set of customizable attributes that summarise the customization of the *core product* but not of the *augmented product*. Consumer research has recognised there is more to a product than the item the consumer takes delivery of. Levitt (1980) conceived of the *augmented product* concept which has come to be defined as:

> *'the view of a product that includes not only its core benefit and its physical being, but adds other sources of benefits such as service, warranty, and image. The augmented aspects are added to the physical product by action of the seller, e.g., with company reputation or with service'*[12]

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[11] The term *customizable attribute* is preferred to *customization dimension* for two reasons. Firstly, it is to avoid confusion since 'dimension' is identified as one of the customizable attributes (see later) and, secondly, in the language of consumer behaviour, products are described in terms of attributes rather than dimensions.

[12] http://www.marketingpower.com/live/mg-dictionary-view211.php

Augmented attributes as well as core attributes can be customized. In relation to the automotive sector Alford *et al* (2000) identify three categories of customization – *core*, *optional* and *form* – and their illustration of *form* customization is of augmented attributes:

> *'Distributors offer a package of services that help to differentiate the vehicle from their competitors, and tailor the sale to the needs of the customer. These packages include financing options, warranty and service options, insurance and membership with recovery services.'*

Augmented attributes are excluded from the scope of the customizable attributes addressed in this chapter, not because they are considered to be less important, but because the focus of the research is the production of customized products and hence on the operational challenges of customizing the core attributes.

5.2 Set of generic customizable attributes

The development of the set of attributes has been a progressive process, involving the synthesis of information and ideas including the ways in which products have been, are being and could be customized. The set presented in Table 5:1, has been developed, expanded and refined over time.

Often the customization of a product involves customizing a mix of attributes, e.g. tailoring a suit is a combination of dimensional, style and grade customization. Furthermore, one component may affect multiple attributes. For example, cashmere is perceived to be a high grade material for suits but is less hard wearing – a whole product property - than lower grade materials.

Table 5:1 Customizable product attributes

Customizable attribute	Description
Dimensional fit/size	Part or all of the product is adjusted, cut or scaled to fit the dimensional requirements specified by the customer
Hardware functionality	The functional capability of the product is altered by changing, adding or subtracting hardware
Software functionality	The functional capability of the product is altered by changing, adding or subtracting software, by altering or replacing the programming in the product
Property of the whole product	Altering or changing properties that relate to the product as an entity, for example, corrosion resistance, vibration characteristics, noise emission or comfort
Grade	This relates to the quality category of a product, such as solid silver or silver plated. There may be objective or accepted standards that define categories or it may be subjective but possibly can be benchmarked. It is probable that altering the grade of a product will also alter another attribute.
Quality level	This concerns measures such as reliability, tolerances, precision
Aesthetics and style	Changing the shape, look or feel of a product, such as by selection of interior décor for a vehicle. Typically colour will fall into this category but colour may also fulfil other customization requirements such as functionality or personalisation
Identification and personalization	Altering a product by adding a unique identifier for corporate customers or an individual customer, for example, embroidering and individual's name on a garment, adding a corporate logo to a product or altering the colour (livery) of a product
Literature	Documentation is an important part of the product-service package for many consumer and industrial products and must often be customized for the specific product variant, specific market or specific type of customer
Packaging	Many products are differentiated by packaging. Customization may mean changing packaging design, appearance, physical performance or functionality, but can also mean packing other items with the product

5.3 Categorisation of the products from case study companies

The attributes by which products of the five companies for which field studies were undertaken are customized are identified in Table 5:2. This small sample shows a wide range and significant diversity with one company customizing two attributes and another eight. The spread of results gives an immediate impression, in qualitative terms, of differences across the companies.

Table 5:2 Product attributes customized by each manufacturer

Manufacturer	European bicycle	Computer assembler	Mobile phone	Commercial vehicle	Office furniture
Dimensional fit/size				✓	✓
Hardware Function		✓		✓	✓
Software Function		✓	✓		
Property of the whole product				✓	✓
Grade	✓	✓		✓	✓
Quality level					
Aesthetics and Style	✓			✓	✓
Identification and Personalization			✓	✓	✓
Literature			✓		✓
Packaging		✓	✓		✓

It was found as the research progressed that identifying and understanding the attributes on which an enterprise offered customization provided a framework for gathering information about customization practices and the business environment. Table 5:3 summarises the situation of the office furniture company, giving ratings of the frequency of attribute customizations and of the match between customization offered and demand from the market. This company judged that it offered the right amount for most attributes and was able to offer more than the market required on two of the attributes.

The situation of the commercial vehicle manufacturer is presented in

Table 5:4. As well as offering a catalogue of customizations, this company was open to suggestions from its customers and these were referred to as *special* customizations. The company judged the three most common motivations for requesting a special customization were *hardware function, style* and *personalization*. The first of these – hardware function – was requested even though there were *very many* choices in the standard range, which demonstrated that customers had specific and changing needs that were difficult to satisfy with generic options. Although a less frequent request, *dimensional fit* followed the same pattern, with special dimensional requirements being requested even though there were *very many* choices in the standard range. Unfortunately for the company, increasing the envelope of dimensional customization was a challenge in terms of engineering and production difficulties, with them rated as *difficult* and *very difficult* respectively.

None of the five companies customized the *quality level* attribute. What is more, no example of this customization has been identified since the development of the attributes. The quality level of the augmented attributes of products are observed to be customizable – with examples being the options of extended warranties; quicker/slower breakdown response; access to a helpline during the working day or 24/7.

Table 5:3 Customization profile of the office furniture company

Customizable attribute	Frequency of customization	Comment	Is the customization potential of the product more or less than demanded by customers?		
			More than	Correct amount	Less than
Dimensional fit/size	Every order	All ustomers choose backrest height, seat width, and chair height		✓	
Hardware Function	Every order	All customers choose movement options such as: static, swivel, castors, armrest, coat hanger		✓	
Software Function	N/A				
Property of the whole product	Some	Heavy duty options are selected by customers seeking chairs for use in 24/7 environments		✓	
Grade	Every order	Every customer chooses the grade of fabric	✓		
Quality level	Never			✓	
Aesthetics and Style	Every order	All customers create the aesthetic of the product by the choice of options and fabric combinations	✓		
Personalization	Every order	All customers choose colours and finishes. Some request use of material with their logo		✓	
Literature	Some	Customers have a choice of how the literature is attached to the product (in a pocket or hanging)		✓	
Packaging	Some	Packaging is tailored for some customer s		✓	

Table 5:4 Assessment of 'special' customization by attribute type (commercial vehicle manufacturer)

Attribute type	[1]Customer motivation for requiring a 'special' customization	[2]Amount of choice in standard range	[2]Amount of choice in 'specials' range	[3]Engineering difficulty in increasing customization	[3]Production difficulty in increasing Customization
Dimensional fit	Occasionally	Very many	Some	Difficult	Very difficult
Hardware Function	Often	Many	Many	Average	Average
Property of the whole product	Occasionally	Many	Many	Difficult	Difficult
Grade	Occasionally	Low	Some	Average	Average
Aesthetics and Style	Often	Low	Many	Relatively easy	Difficult
Personalization	Often	None	Some	Relatively easy	Average

1: Never, Rarely, Occasionally, Often, Always
2: None, Low, Some, Many, Very many
3: Relatively easy, Average, Difficult, Very difficult, Impossible

5.3.1 Linkages between attributes and operations

Each of the companies is reviewed for linkages between customizable attributes and their operations, in regard to two aspects:

- implications of altering / increasing the customization of an attribute; and
- method of fulfilling orders for that form of customization.

For the first, the implications to internal order fulfilment processes and the external supply system are rated. If it is judged that either would require more than slight modification or re-organisation, a link is made (signified by a tick ✓ in Table 5:5). In terms of the method of fulfilling orders, the attribute is linked to one or both of process flexibility and inventory and a link must be made with at least one.

The sample set is too small to justify concluding the existence of strong patterns in the linkages, therefore only general observations are made. The first is that assembly operations are a key part of the order fulfilment process for all of these companies, and in all cases the majority of components are sourced from external suppliers. The bicycle, office chair, computer and mobile phone have a high degree of modularity and it is not surprising that for all of these companies at least a proportion of their product customizations are facilitated by holding inventories of components. In the case of the office chair, all but one of its eight customizable attributes is supported solely by holding inventory.

Does the importance of flexible processes and the need for modifications to the internal and external systems, indicate that the commercial vehicle is the least modular product? In terms of design effort, number of manufacturing processes, and number of suppliers and components, the commercial vehicle is the most complex product studied, and perhaps subject to the greatest level of regulatory constraints, placing pressure on engineering and product specification functions. The automotive sector has been pursuing supply chain initiatives such as *JIT* and *lean* and it would be surprising if customization were facilitated by holding inventory. In conclusion, the difference between it and the other four cannot be put down to a single factor such as product modularity.

Table 5:5 Linkages between customizable attributes and operations

Manufacturer	Introducing a customization		Ongoing fulfilment	
	Internal process mod	External supply mod	Process flexibility	Inventory
European bicycle				
Hardware function				✓
Grade				✓
Aesthetics and Style				✓
Computer assembler				
Hardware Function				✓
Software Function			✓	
Grade				✓
Packaging		✓	✓	✓
Mobile phone				
Software Function			✓	
Aesthetics and Style			✓	✓
Identification and Personalization				✓
Literature			✓	
Packaging	✓		✓	✓
Commercial vehicle				
Dimensional fit/size	✓	✓	✓	
Hardware Function	✓	✓	✓	✓
Property of the whole product	✓	✓	✓	✓
Grade		✓	✓	✓
Aesthetics and Style		✓	✓	
Identification and Personalization		✓	✓	
Office furniture				
Dimensional fit/size				✓
Hardware Function				✓
Property of the whole product				✓
Grade				✓
Aesthetics and Style			✓	✓
Identification and Personalization				✓
Literature				✓
Packaging				✓

5.4 Identifying which attributes to customize

From an operations perspective it may be feasible to offer customization across many or all of the attributes. It is probable the greater the amount of customization carried out, the greater will be the investment needed and/or the greater the variable cost per customization (when volume is constant).

Even if cost is not a concern, the challenges of communicating the customization potential to the customer/consumer and the risk of more choice creating confusion are also reasons for why a producer will wish to know on which attributes to offer customization.

A conceptual approach to identifying the key attributes to customize is described here. It starts by asking customers to assess the value of each of the unique product configurations that could be created within a product family. If a customer were asked to do this, they would judge some configurations to be of higher value than others. If another customer rated all configurations, they may give different valuations to the first customer, and if a third customer undertook this exercise they may give yet another pattern of ratings. Figure 5:1 illustrates the value assessments of three customers shown as smooth plots, which is unlikely in a real exercise but helpful for explaining the concept.

Figure 5:1 Conceptual illustration of customer differences

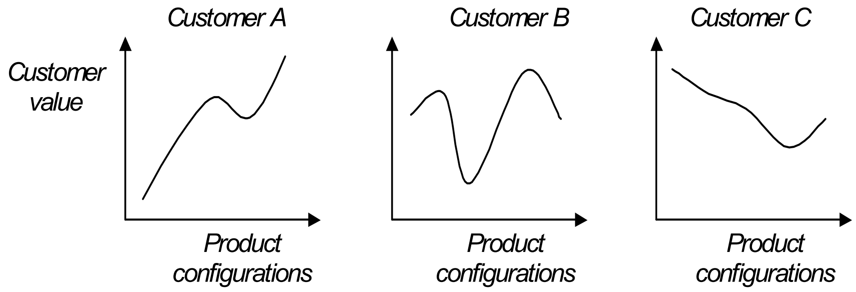
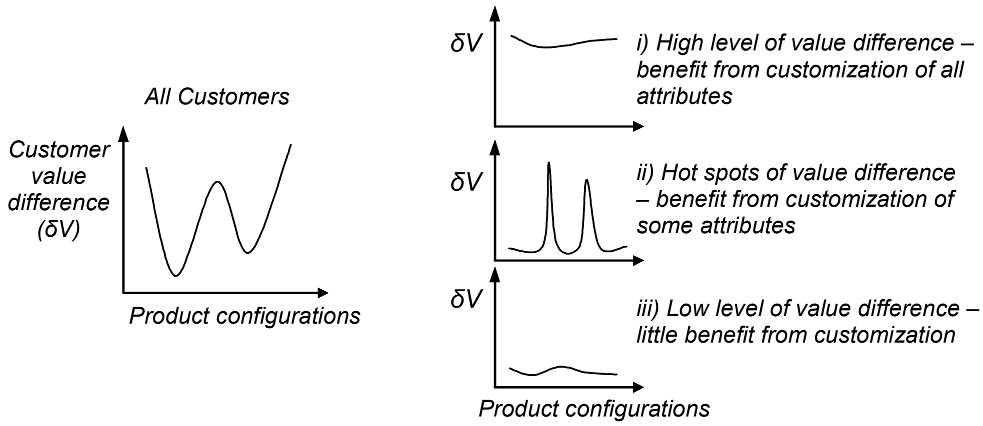


Figure 5:2 The conceptual δvalue curve with interpretations



The identification of customizable attributes comes from analysing the differences between the value curves. By comparing all customers, a Value Difference curve (δV) can be constructed (Figure 5:2) and it is the shape of this curve that reveals the value enhancing potential of specific customizable attributes.

If the δV curve is high across the entire set of product configurations (plot (i) in Figure 5:2) it indicates that customers do not share the same perceptions of the product. In any given set of customers there will be diversity in the configurations that are valued highest. The producer would be best advised not to try and anticipate which configuration a customer is seeking, but to consult the customer about how the product should be configured in regard to all attributes – i.e. all attributes are customizable.

A uniformly low δV curve (plot (iii) in Figure 5:2) indicates there is little difference in how product configurations are valued by customers. In other words, from one customer to the next there is strong agreement in how the product is perceived and the producer can study the original value plots (illustrated by Figure 5:2) to identify the most attractive product configurations.

A δV curve with a mix of peaks and troughs (plot (ii) in Figure 5:2) is indicating that a producer should consider customizing only the attributes that create the differences.

5.5 Discussion of the customizable attributes

The set of ten customizable attributes that has been synthesised is consistent with the empirical data analysed but only through continued testing against customized products will this be assured. Eight of the attributes are concerned with the customization of the product, and two are concerned with essential elements of a product – its packaging and accompanying literature.

With the sample of products analysed it is not feasible to identify general relationships between attributes and operations and it is conjectured that the links will depend on the nature of the product and the process technology used and therefore be specific to sectors and situations. The linkages will be important to the producer, especially at the stage of evaluating the feasibility of customization. The set of customizable attributes can be used as prompts at the planning stage when product customizations and process options are being considered.

The implication of customizing an attribute to the operations processes is one of three links that a producer should be concerned about. The two other links are:

- Links with product design – i.e. how do the customizable attributes map onto the components and facets of the product?
- Links with customer needs – i.e. do these customizations satisfy customer wishes?

The first of these is addressed by design methodologies and the QFD technique. The second is also addressed to some degree by the QFD methodology but overall it is a less developed issue. This chapter has also presented a conceptual approach using the δV curve that addresses part of this question but there are other aspects, in particular how to assure that the customer's requirements are being addressed by the customizations they have selected? This is a quality assurance (QA) problem and various off-the-shelf QA techniques are available for assessing and testing a design against a specification, such as failure modes and effects analysis (FMEA), reliability assessment methods, hazard and operability analysis (HAZOP). These methods focus on *quality level* and *function* and to some degree *whole product properties*. They are not suited to addressing the customizable attributes of *aesthetics and style*, *dimensional size/fit*, *personalization*, or *quality grade* that can have a subjective element. Involving the customer actively in reviewing the product is a tactic for these attributes, but is not straightforward. One approach to involving the customer is to give them the bill of materials (BOM) and another is to pass to them the product drawings. Both approaches place demands on the customer and may be acceptable if the customer is a professional buyer for (say) a specially customized product for a retail outlet, but when dealing with consumers such methods could turn them away and not reduce the uncertainty. A superior way of tackling the *dimension* attribute is to make a (scale) model or prototype of the product. It is a method that suits also the review of the *aesthetics and style* of the product and how any *personalization* is executed. Developments in the technologies of rapid prototyping and virtual reality (VR) are opening up new options and Ottosson (2002) describes VR as offering 'an accurate and detailed method of communicating concepts to customers/users' and notes that it is good for aesthetic and ergonomic design aspects.

How the case study companies assure the customized design was not studied systematically but it is worth noting:

- three of the companies produced detailed catalogues, either in paper or web form;
- two would prepare detailed specifications for some customers prior to manufacture;
- four companies would produce a prototypes if they judged it beneficial to do so.

The development and use of the customizable attributes is an evolving process and there is scope for further study and appraisal.

Chapter 6
Review of literature and research agenda for the VBTO study

Abstract

This chapter is concerned with the second goal of the research, namely the study of the Virtual-Build-to-Order fulfilment model. The context for, and relevance of the study are first discussed. Then relevant research literature is reviewed and analysed. From this analysis a set of research questions is developed.

6.1 Introduction

Mass Customization (MC) is not a mature business strategy. A number of operational sub-strategies are being used as illustrated by the case studies summarised and studied in Chapter 3 and Chapter 4, and it can be expected that different order fulfilment models are also in use. An order fulfilment model referred to as Virtual Build-to-Order (VBTO: Agrawal *et al* 2001), which is of relevance to one of the MC modes - Catalogue MC - is the focus of attention in the remainder of the thesis.

Catalogue MC is the mode in which a customer order is fulfilled from a pre-engineered catalogue of potential variants that can be produced with a fixed order fulfilment process. In this mode product design and engineering are not linked to orders – they will have been completed before products are offered on the market and before orders are received. Likewise the order fulfilment activities will have been designed and engineered ahead of any order being taken.

In the Catalogue MC mode, customers select from a pre-specified product/ variant/ option range and the products are manufactured and delivered by the order fulfilment activities that are in place. This mode is relevant to consumer and Business-to-Business applications. If the design of the product is completed after consultation with the customer, or the order fulfilment system is modified for an order, then the mass customizing company is not operating in the Catalogue MC mode but in one of the other four modes.

Even when limiting the focus to the Catalogue MC mode there is no reason to believe that organisations are constrained to one model of how to achieve it operationally. Companies are approaching MC in general and the Catalogue mode in particular either from a mass production or a pure customization origin (Duray 2002). This in itself is reason to believe that several order fulfilment models will be observable in practice. The review in this chapter finds the differences to be sufficiently pronounced to organise the reported models into four structural categories:

- fulfilment from stock;
- fulfilment from a single fixed decoupling point;
- fulfilment from one of several fixed decoupling points;
- fulfilment from several locations, with floating decoupling points.

The purpose of the review is to place in context the model that will then be studied – the VBTO model – which fits into the last of the four structural categories. Why focus on one model and why VBTO? Firstly, there are a number of factors that make VBTO an interesting and worthy model to study:

- it is a fulfilment model that is new. The concepts within VBTO can be seen in fulfilment models used in the machinery and capital goods sectors but it is new to mass marketed products. It is being enabled by developments in information technology, particularly real

time material tracking and integrated information system, which are only now making it feasible.
- it is being used by the automotive sector, an important, substantial and influential sector. Passenger vehicles are high ticket items, produced in volume and there is a strong desire to shift from a push strategy (i.e. Make-to-stock) toward a pull strategy (i.e. Build-to-order). VBTO is attractive to mass volume automotive OEMs and it is being adopted (Holweg & Pil 2004).
- it is a model that has been studied little.

A second reason for focusing on one order fulfilment model is that it is not practical to research all of the models being applied to Catalogue MC, or to attempt to synthesise a generic MC order fulfilment model that has elements from all.

As well as placing VBTO in context the literature review also considers factors internal and external to an order fulfilment process that inhibit or facilitate MC fulfilment. These are analysed under the following headings:

- product variety;
- postponement;
- process flexibility;
- the logic of how products are allocated to customers;
- customer factors that influence order fulfilment process design and operation.

Following the literature review a research agenda is presented.

6.2 Literature review

6.2.1 Delineating the order fulfilment process

Order fulfilment is not a universally used term as noted by Kritchanchai & MacCarthy (1999) who found:

'few sources in the literature discussing the details of the order fulfilment process explicitly'.

There is no standard definition of order fulfilment and no common understanding of what activities it involves. While this grants freedom in defining the term it also means there is no readily identified pool of literature awaiting review – relevant literature may be found under a variety of headings.

In the context of manufacturing, it is intuitive to say that order fulfilment involves the hand-over of material to the customer. Beyond this it is less certain as to what should be treated as part of the order fulfilment process (OFP). To Shapiro *et al* (1992) the details vary from industry to industry but in general they see fulfilment as encompassing procurement, manufacturing, assembling, testing, shipping and installation. For them it does not include order entry. If the goal of order fulfilment is specified as complying with the customer's requirements, in particular the WHWW details (What product(s), How many, Where to deliver to, When to deliver) then the OFP is not involved directly with the customer to take the details of the order. Shapiro *et al* (1992) exclude order planning, order selection and scheduling from their fulfilment stage, although they argue fulfilment can require considerable co-ordination. However, it is argued here that to comply with the WHWW details not only must OFP encompass some material processing/ transportation activities but also some element of control logic to plan and prioritise as well as co-ordinate activities.

At one extreme the logic may be a simple rule about which product to take from the shelves and the activity be nothing more than handing it over to the customer. At the other extreme the OFP may involve the triggering and sequencing of complex production and distribution processes. Therefore, while the details and scale of the OFP from one situation to another might differ greatly, in general terms the OFP encompasses the material processing activities concerned with complying with customer instructions and the control of these activities.

It is tempting to use the Customer Order Decoupling Point (CODP), which is 'traditionally defined as the point in the manufacturing value chain where the product is linked to a specific customer order' (Olhager 2003), to delineate the OFP. However, although activities upstream of the CODP are controlled by forecasts or replenishment policies, the state of these activities can have a bearing on the future performance of the downstream activities. This is particularly relevant when customer orders are conditional on delivery dates promised during the sales negotiation. In some manufacturing systems the upstream and downstream activities could be insulated from each other but, in general, there may be dependencies between them. If the customer's WHWW requirements are to be fulfilled, the OFP must have good situational awareness of the system – i.e. a grasp of the current state of the material processing activities, how they got into this state and, more importantly, how they are going to develop over time. For this to be the case the OFP cannot be blind to the upstream activities and, consequently, it is not always appropriate to use the CODP as an OFP boundary marker.

The process of Demand Management, as described by Vollmann *et al* (1997) perhaps provides a template for defining and describing OFP. To Vollmann *et al* demand management is a highly integrative activity that captures and co-ordinates demand on manufacturing capacity. They say:

> *'the basic concept of demand management is that there is a pipe of capacity which is filled in the short run with customer orders and the long run with forecasts; order entry is a process of consuming the forecast with actual orders'.*

To them it encompasses forecasting, order entry, order-delivery-date promising, customer order service, physical distribution and other customer-contact-related activities.

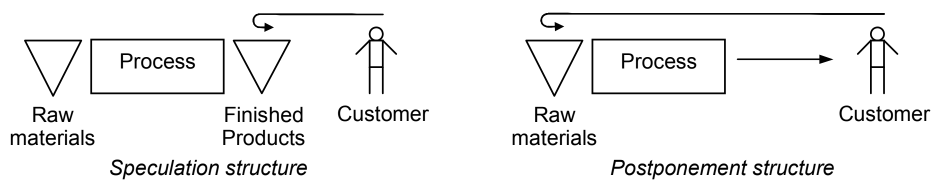
In this review, order fulfilment is interpreted in the following way:

- The OFP receives and acts upon customer orders, which contain the WHWW details (What product(s), How many, Where to deliver to, When to deliver);
- The OFP requires an awareness of the current and future state of the material processing activities. It envisages a pipeline of real and planned products and, using control logic, links customers to either type of product;
- The activities upstream of the CODP are within the bounds of the OFP if downstream activities are dependent on their performance.

6.2.2 Order fulfilment structures for Catalogue MC

The relative positions of processes and inventories are a fundamental aspect of order fulfilment models, as illustrated by Bucklin (1965) in his comparison of the speculation and postponement strategies. Compared to the speculation model, the stock of finished goods is not a component of the postponement model (Figure 6:1).

Figure 6:1 Speculation and Postponement structures (Bucklin, 1965)



Reviewing the fulfilment structures finds four structural forms that are used in Catalogue MC and related contexts:

- fulfilment from stock;
- fulfilment from a single fixed decoupling point;
- fulfilment from one of several fixed decoupling points;
- fulfilment from several locations, with floating decoupling points.

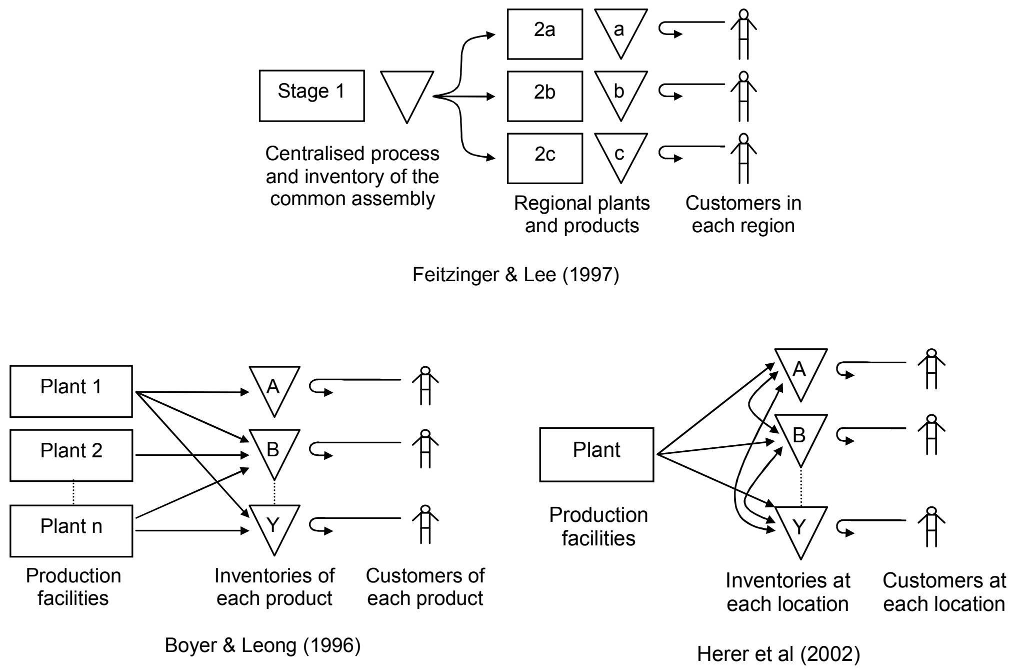
6.2.2.1 Fulfilment from stock

Product variety has been on the increase in many consumer goods segments (Cox & Alm 1998) and since fulfilment from stock is still prevalent for these types of products it is unsurprising that some examples can be found of this configuration being adapted to high variety / mass customization situations.

There is a degree of uncertainty over whether to include these stock fulfilment models in the review and which papers qualify for inclusion. The customization of printers by Hewlett Packard (Feitzinger & Lee 1997, Lee & Billington 1995) has been heralded as mass customization but the end customer is not involved in the process. The customization is required for the region in which the printer is to be sold and hence the study could be relabelled as solely a case-study in postponement. It is included in the review, along with two other examples, to show the diversity of approaches for coping with high product variety. The three examples are summarised below and in Figure 6:2:

- Hewlett-Packard printers are customized for each region by postponing some assembly and packaging activities. Standard unfinished units are shipped from a central facility to each region for completion (Feitzinger & Lee 1997, Lee & Billington 1995).
- In the context of the automotive sector Boyer & Leong (1996) study a structure in which multiple product types are supplied to many stock locations. They study the impact on the system of increasing the number of products that each plant can produce.
- Herer *et al* (2002) examines the method of transhipment for high variety of products, which is the ability to transfer stock between locations at the same echelon level. Transshipment is a form of physical postponement and as Herer puts it, creates the ability to transform a generic item (an item at any location) into a specific item (an item at a specific location) in a relatively short time.

Figure 6:2 Structures for fulfilment from stock



A theme of the research into stock fulfilment structures is how to structure the processes that replenish the stock to cope with variety without suffering high costs. Hau Lee is one of the principal contributors in this area and he sees a key issue to be how product design interacts with the process (e.g. Lee & Billington 1995, Lee 1996, Lee & Tang 1997, Lee & Tang 1998, Whang & Lee 1998). Whang & Lee (1998) present models to indicate the scale of benefit that postponement can bring through uncertainty reduction and reduced forecasting error. Lee & Tang (1997) use a model to study three approaches to delaying product differentiation, taking forward the models of Lee (1996). Lee & Tang (1998) study further the approach of *operations reversal* and put forward properties that an order fulfilment sequence should strive for when the major source of demand uncertainty lies in the option mix and the total demand for all options is fairly stable.

6.2.2.2 *Fulfilment from a single fixed decoupling point*

This structure takes the form of the postponement model described by Bucklin (1965, see Figure 6:1). Of the four types of OFS structures this is the format that tends to be associated with catalogue mass customization. In this structure the producer holds stocks of raw materials or part-finished products that are, once an order is received, taken forward to be completed and delivered to the customer.

A standard classification of order fulfilment systems includes a set of fixed decoupling point structures: engineer-to-order (ETO); make-to-order (MTO); and assemble-to-order (ATO). Hill (1995) extended this by adding design-to-order and make-to-print. Recently, the category of configure-to-order (CTO) has been distinguished as a special case of assemble-to-order (Song & Zipkin 2003), in which components are partitioned into subsets from which customers make selections (e.g. a computer is configured by selecting a processor from several options, a monitor from several options, etc).

Many practicing mass customizers have one decoupling point and fit into the assemble-to-order or configure-to-order categories, though they can also perform some fabrication:

- Kotha (1995) describes the Japanese bicycle company, National Panasonic, who await each order before fabricating the frame and assembling the bicycle with components from stock;
- A series of articles describe how the UK company, RM, switched its computer supply business from a make-to-stock to an assemble-to-order fulfilment mode (Duffel 1999, Duffel & Street 1999).
- Orangebox UK is a company producing office furniture. Their products are modular and they produce high levels of variety in small batch sizes. Once an order is received they cut and sew the covers and assemble the product (Tozer 2003).

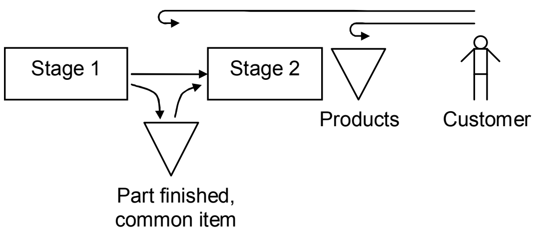
In a high product variety environment, Dobson & Stavrulaki (2003) analyse the switch to a finish-to-order strategy from MTS strategy. The company produced dozens of intermediate products that were then cut into hundreds of sizes and shapes. Orders were received from many dealers dispersed across the US. Although set-up costs would rise, the switch was beneficial in terms of stock costs.

6.2.2.3 *Fulfilment from one of several fixed decoupling points*

These structures have more than one decoupling point, i.e. there are two or more distinct stock holding locations among the production and delivery processes from which raw materials or part-finished products can be taken, allocated to a customer, finished and delivered. A customer need not be aware of which decoupling point is being used for their order.

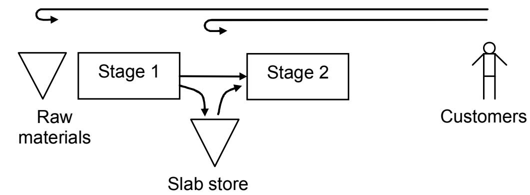
Graman & Magazine (2002) study an OFP with two fixed decoupling points – one is mid process and the other is the finished stock (Figure 6:3). They conclude that holding some items in a part-finished state and retaining some final processing capacity open to fulfil orders can bring significant performance benefits, compared to a situation in which all orders are filled from stock.

Figure 6:3 Structure studied by Graman & Magazine (2002)



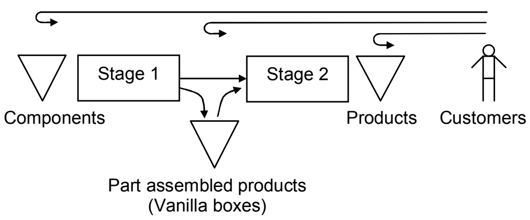
For an Integrated Steel Mill (ISM), Denton et al (2003) develop a model to select which steel slabs to hold in a mid-process inventory (Figure 6:4). Competitive pressure from mini-mills has been forcing ISMs to shift to the high-end markets for exotic or custom-finished steel products. ISMs used to operate in the MTO production mode, with processes designed for high volumes and order fulfillment times in the range of 10 to 15 weeks, but the high-end markets demand custom products with shorter and reliable delivery lead times, in the range of 5 to 6 weeks. The result of increased product variety has been capacity shortages and exploding inventory levels. Prior to implementing their model, 57 slab designs covered about 17 percent of total annual order volume, and after implementation 50 slab designs covered about 50 percent of the total annual order volume.

Figure 6:4 Structure studied by Denton et al (2003)



Swaminathan & Tayur (1998) study an OFP with three fixed decoupling points – one at the start of final assembly, one mid-assembly and finished stock (Figure 6:5). They develop a model to tackle a problem in which a producer offers a broad product range but in each time period orders are received for a fraction of variants only. They compare a *vanilla box* strategy (in which sub-sets of components are pre-assembled into a number of vanilla boxes, exploiting the inherent commonality in the product family) against MTS and ATO strategies (and mixes of the three) and find the vanilla box approach can be superior significantly. In exploring their model, they show how factors including capacity constraints, demand correlation, number of vanilla box types and breadth of product range alter the performance of each strategy. In a second study, Swaminathan & Tayur (1999) go on to develop models that take account of assembly precedence constraints, in particular the feasibility of a vanilla box in terms of whether it can be assembled.

Figure 6:5 Structure studied by Swaminathan & Tayur (1998, 1999)



6.2.2.4 *Fulfilment from several process points, with floating decoupling points*

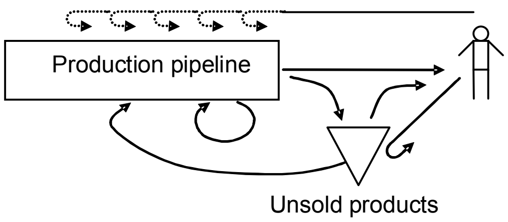
The key feature of order fulfilment systems with this structure is that products can be allocated to orders at any point along the process, hence the coining here of the term *floating decoupling point*. This structure is observed in the capital goods sector but is being adopted elsewhere including the automotive sector.

Manufacturers of complex goods with relatively long production lead times, such as machine tools, have been facing the challenges of increased product diversity and shortening of delivery lead times. The requested delivery lead time is often less than the sum of purchasing, fabrication and assembly lead times. As a consequence such companies have been developing their order fulfilment processes. In their study of three heavy manufacturing firms Raturi *et al* (1990) describe how firms have implemented a build-to-forecast (BTF) schedule in which they forecast end-product mix, create a master schedule of end-products and then release production orders before specific customer orders are received (Figure 6:6). In BTF there is no stopping point in the production process so mid process buffer inventories are avoided. Customer orders are matched to items in any state of production that will meet the due date. Customer orders rarely match the end products being built hence orders are fulfilled by:

- changing products early in the process if the basic model is an appropriate one and the production plan can be altered to accommodate the actual order;
- reconfiguring an end product, with features removed and replaced as required. On occasion the changes are so extensive that a loss is incurred.

Bartezzaghi & Verganti (1995a, b) study a market for capital telecommunications equipment in which there are a small number of large and powerful buyers. A manufacturer expects contracts to be issued but the volume and specification is uncertain, and some degree of manufacturing must be initiated so as to be in a position to meet the delivery schedule.

Figure 6:6 Structure studied by Raturi et al (1990)



The development of information systems and product tracking technologies has led automotive fulfilment processes to evolve into this type of structure. The multi-mechanism system has been labeled *Virtual Build-to-Order* and Agrawal *et al* (2001) describe it as connecting customers:

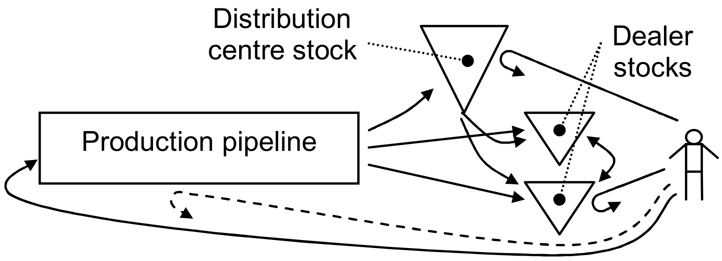
> *'either via the internet or in dealer's showrooms, to the vast, albeit far-flung, array of cars already in existence, including vehicles on dealer's lots, in transit, on assembly line, and scheduled for production',*

with the expectation that:

> *'customers are likely to find a vehicle with the colour and options they most want'.*

Holweg (2000) also describes the multiple fulfilment mechanisms by which a customer can receive a vehicle: from the local dealer's stock; by a transshipment from another dealer's stock; by a vehicle taken from a central stock holding centre; by a vehicle being submitted into the order bank as a build-to-order product; or by a vehicle that is in, or scheduled for, production being allocated to the customer, which may involve its specification being amended (summarized in Figure 6:7).

Figure 6:7 Structure studied by Holweg (2000)



Turner & Williams (2005) use simulation to study the fulfilment model described by Holweg (2000) and find that holding finished stock at a distribution centre rather than at the dealers brings superior performance in terms of customer fill rate. They also find that giving dealers the ability to amend some features of a vehicle (such as alloy wheels, fog lights, satellite navigation and alarm) brings a small but significant benefit.

6.2.3 Fulfilment influences

6.2.3.1 Product Variety

Product variety is increasing, evidenced by data (Cox & Alm 1998) and by the initiation of research into the challenges created by product variety (Ramdas 2003). High levels of product variety tend to go hand in hand with a mass customization strategy (e.g. Denton et al 2003, Swaminathan and Tayur 1998).

From the literature it is evident that product variety creates challenges for the design and operations functions (see the review by Ramdas 2003). Even if not from a customization context, much of the literature on product variety has some relevance to order fulfilment. The aim here is not to review the literature on variety to draw out general lessons – such reviews have been done - but to review the literature that has addressed product variety in an MC or related context. In one sense most, if not all of the papers reviewed in this chapter could be classified as addressing product variety. Here, two papers are identified that are particularly relevant.

McCutheon et al (1994) discuss the implications of what they term as the 'customization-responsiveness squeeze' for manufacturers of capital equipment, and machine tools in particular.

Among the coping tactics for a manufacturer, they note: increasing the flexibility of the process; altering the product design (i.e. designing for postponement); managing demand including how sales link to the production planning process; and following a build-to-forecast (BTF) approach.

Salvador & Forza (2004) also look at implications of the customization-responsiveness squeeze to the whole enterprise and find that customized variety creates difficulties in the areas of sales, technical office functions (e.g. documentation) and manufacturing.

6.2.3.2 Postponement

Delaying the completion of the product until a customer order is received is a tactic used in many MC applications summarised in section 6.2.2 above.

A recent review of postponement distinguishes several forms: product development postponement, purchasing postponement, production postponement and logistics postponement (e.g. Yang & Burns 2004). All forms are relevant to MC but product development postponement is not relevant to Catalogue MC as this is a mode in which the product is fully engineered before the customer order is taken.

Postponement and a modular product are two approaches often presented as being essential for MC. For example, Partanen & Haapasalo (2004) state:

> *"The fundamental idea behind mass customization and modularization is that the order penetration point is delayed as late as possible."*

However, the review of fulfilment models above identified MC applications where customers are fulfilled from stock as well as from part-finished products, and VBTO is one such model. These applications refute the claim that postponement is essential.

6.2.3.3 Process Flexibility

In environments of high product variety and customization, the characteristic of *flexibility* is highlighted in the literature as being the key facilitator/inhibitor. Several sources consider flexibility to be an enabler of mass customization (Fogliatto *et al* 2003, Da Silveira *et al* 2001, Kakati 2002, Duffell & Street 1998) and the ability to be flexible is assumed within analyses of the economic impact of mass customization (de Vaal 2000, Norman 2002). A wider range of products and increased customization are identified by De Toni & Tonchia (1998) as two of five motivations for flexibility, the others being: variability of demand (random or seasonal); shorter life-cycles of the products and technologies; and shorter delivery times.

There is a considerable body of flexibility research. The breadth of the topic is vast, being approached at one end as a concept and at the other examined in the context of specific situations. The scale of concern ranges from the flexibility of a sector down to the flexibility of a machine or fixtures and the concept also has a temporal property – flexibility over a short or long time horizon. Although wide ranging, there is little that focuses on the flexibility of mass customization systems specifically within the large volume of literature. This is not to say that flexibility has not been of interest in mass customization research. For many of the studies referred to above, flexibility has been implicit but has not been the primary focus of the studies.

Four studies have been identified that assess process flexibility and are relevant to VBTO.

Bradley & Blossom (2001) estimate the change in cost and the improvement in delivery lead time that would be achieved by an assembly process if it were to accept a higher proportion of customer orders. The study is in the automotive sector and the order fulfilment process under consideration resembles a floating decoupling point system. The study does not look at how customer orders are matched to vehicles in the pipeline, but recognizes this is an area that needs attention. Their supposition is that flexibility can be increased in the assembly line by adding production capacity (people or equipment) so that a fluctuating mix of products can be produced. Thus the products made on the assembly line can be those that the customers want, when they want them, rather than units selected for attainment of maximum efficiency. By simulating a generic automotive system they estimate, in the worst case, cost would rise by around 0.017% at a level of 70% make-to-order (a significant reason being that direct labour accounts for only 6% of costs typically) and delivery lead times would reduce by around 70%.

Bukchin *et al* (2002) develop a heuristic for designing assembly lines for mixed model operations. They assume the model-mix is determined ahead of time and stable (say for a year ahead) but the sequence of launching products to the line must be determined by actual short range demand patterns and customer orders. Their approach assumes a model mix for which the combined workload is balanced for the duration of the entire shift and not on the basis of station cycle times (as was the case for single model assembly).

Boyer & Leong (1996) develop a model for evaluating the benefit of increasing levels of flexibility. Their context is the automotive sector and the point of interest is the ability for a number of plants to produce more than one product line. Without flexibility, unused capacity in one plant cannot be used to fulfil demand that exceeds the capacity of another. They find that opening up a fraction of the feasible cross-links between products and plants brings substantial gains in overall performance, even with a throughput loss of 20% due to changeovers.

To counter supply chain effects, the Quantity Flexibility (QF) contract has become popular (Tsay & Lovejoy 1999). It attaches a degree of commitment to the forecasts by installing constraints on the buyer's ability to revise them over time. The extent of revision flexibility is defined in percentages that vary as a function of the number of periods away from delivery. The QF contract formalizes the reality that a single lead time alone is an inadequate representation of many supply relationships, as evinced by the ability of buyers to negotiate quantity changes even within quoted lead times. The model indicates that inventory is a consequence of disparities in flexibility. In particular, inventory is the cost incurred in overcoming the inflexibility of a supplier to meet a customer's desire for flexible response and they coin the term *flexibility amplification.* All else being equal, increasing a supply chain participant's input flexibility reduces its costs and promising more output flexibility comes at the expense of greater inventory costs.

6.2.3.4 Fulfilment logic

The issue of how to link orders to products or production capacity is a key aspect of Demand Management. Rules such as assigning orders to the 'earliest available' and 'latest available' production slot have been examined (e.g. Guerrero 1991). The *production seat system* (Tamura & Fujita 1995, Tamura *et al* 1997, Tsubone & Kobayashi 2002) is a demand management system for producers of a variety of complex products in mixed or small lots, developed for the purpose of shortening delivery lead times. It deliberately creates capacity slots of different dimensions in recognition of differences in product manufacturing requirements and the sales team can see which slots are free when negotiating with the customer.

In their study of using vanilla boxes in the fulfilment process, Swaminathan and Tayur (1998) make the conjecture that it could be cost effective for the producer to supply the customer with a product that has superior grades of component(s) or even include redundant components that the customer may not be made aware of, if the consequence of not doing so is to lose the sale. Giving customers substitutions when there are component or capacity shortages is not a new idea but, as Ramdas (2003) comments.

> *"there has overall been little research that addresses component-sharing issues for components with a strong influence on consumer perceptions."*

Balakrishnan & Geunes (2000) is one of the many studies that examines substitution without distinguishing the two types of component, but a concept they use in their analysis is *conversion costs,* of which they say:

> *"the per-unit conversion cost represents any additional processing effort or cost incurred when we substitute a preferred component with an alternate component."*

The concept is not taken further in their analysis, but it is a concept of interest and is consistent with the concept of reconfiguration cost presented in this thesis (see section 7.1.2, page 58, and Chapter 10).

6.2.3.5 Customer factors

Differences across customers are, of course, the prime reason for the growth in product variety. However, customer differences can be expected to create other forms of 'service' variety within the order fulfilment system, such as different delivery lead times and price.

Price and lead-time are interrelated. Price is connected to value (e.g. Meredith *et al* 1994) and it is well understood that value tends to decay over time (e.g. Lindsay & Feigenbaum 1984). However, the rate of decay is not uniform across customer groups and 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 (Marmorstein *et al* 2003) but the research in the 'to-order' sector is scarce. Tang & Tang (2002) study time-based policies on pricing and lead-time for a build-to-order and direct sales manufacturer of products whose value is decreasing rapidly, such as is the case with high technology components. Although Chen (2001) is not focusing on high variety systems, his work is relevant. He proposes customers be given the opportunity to select from a menu of price and lead time combinations, with greater price discounts on offer for longer delivery times. By reducing the proportion of customers who demand immediate fulfilment, his model shows how safety stock/inventory along a supply system can be reduced.

Evidence from the automotive domain supports the view that customers vary in their attitude and willingness to waiting. From a survey of customers who had bought new cars, Elias (2002) plotted distributions of the importance of waiting time in the purchase decision and of the customer's ideal waiting time, showing a significant range and a significant difference across the customer base.

Figure 6:8 Importance of wait in the decision to buy, Elias (2002)

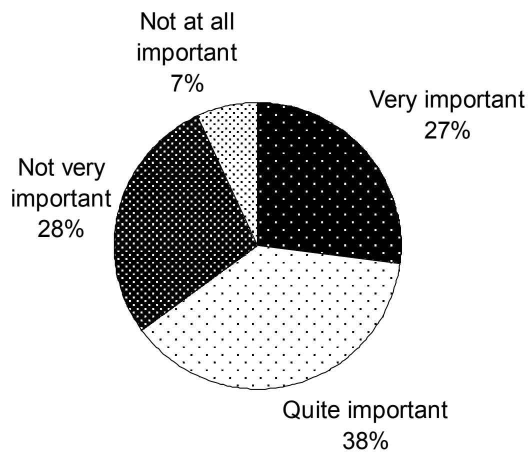
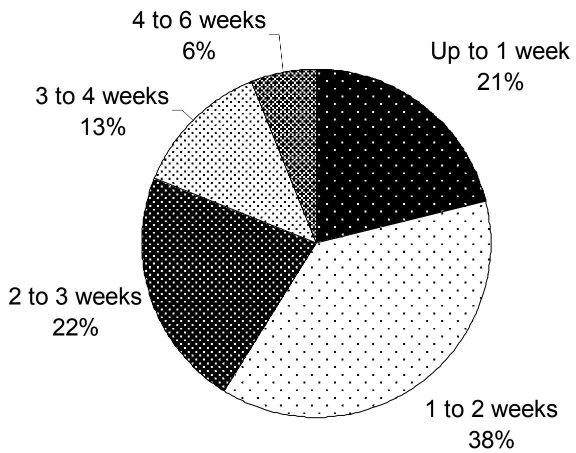


Figure 6:9 Ideal wait from placing the order to delivery, Elias (2002)



Customers can be expected to differ in their attitudes toward specification compromise as well as to delivery time. In an ATO context Iravani *et al* (2003) use simulation to find that customer tolerances to substitutions have an impact on the stock policy of an ATO system. They divide customers into four groups that differ in regard to which components are key and non-key, and which substitutions they are prepared to accept (e.g. a proportion, m, prepared to accept item B instead of A with a proportion, 1-m, lost, and if B is also unavailable a proportion, n, will take C and m-n will also be lost). In their system, customers must get their key items or acceptable substitutions for their key items, but will still purchase if a non-key item is unavailable and cannot be substituted. They use several overlapping measures:

- Fully satisfied – customers getting the exact match for key and non-key components;
- Key satisfied – customer who get all of their key items, but some or all of their non-key items are substituted (note Fully satisfied is a subset of this category);
- Substitution satisfied – customers who accept a substitution for at least one of their key items.

Internal data from Ford provide warnings about specification and delivery time compromise (Hawkins 2002). Post-purchase surveys show late delivery to reduce the proportion of customers who are completely satisfied with their product from 57% to 32%. Fewer customers who bought a vehicle that was not to the exact specification they had targeted would definitely repurchase a Ford vehicle – 25% compared to 39% who had received the exact specification.

6.2.4 Conclusions from the literature review

Diversity in the order fulfilment structures being deployed and being researched for MC and high variety environments was expected and is reported in the literature. As noted previously, product variety has been increasing and mass customization is not a mature operations model, hence evolution and diversity in operations models can be expected. What is apparent is that producers are being imaginative in coping with the demands of high variety, customization and short lead times. These demands have encouraged the relationship between product, process and customer to be re-examined. It has led to the re-engineering of the order fulfilment process to create models with multiple fixed decoupling points and the floating decoupling point structure.

A second observation is that there are many avenues worthy of research. Market conditions and technology are driving the re-engineering of the order fulfilment process but there remains the question as to how these structures and their control logic perform and under what circumstances they offer benefits, in particular where there are customer differences. This is not a new observation. Nearly two decades ago Hendry & Kingsman (1989) pointed out that most of the research into a core area of order fulfilment - production planning – had up to that point been aimed at the needs of make-to-stock companies with the Make-to-Order (MTO) sector being neglected. When searching through the literature it appears that a considerable portion of quantitative research in the to-order area is concerned with scheduling techniques to improve due-date compliance, particularly in capacity constrained job-shop environments. This is biased to the Engineer-to-Order (ETO) and MTO environments, and although the Assemble-to-order (ATO) sector has not been neglected the comment has been made by Song and Zipkin (2003) that research into important aspects of ATO are:

"initial forays into largely uncharted territory"

In his review of product variety from a managerial and practical perspective, Ramdas (2003) concurs. He observes that understanding is progressing on many fronts but there are many opportunities for further work.

The award winning research of Swaminathan & Tayur (1998, 1999) into the use of vanilla boxes in an MC environment using several decoupling points demonstrates the potential benefits of research into order fulfilment and at the same time shows how complex the problem can be.

Although VBTO bears some resemblance to the build-to-forecast approach used for capital goods, the scale of the automotive order fulfilment system in terms of production volume, pipeline length and variety of products is several orders of magnitude greater and this calls into question the validity of transferring knowledge from one context to another. For example, a mainstream passenger vehicle can have of the order of 1 million variants (Holweg 2000) and there can be 3 to 4 months of production in the pipeline, equating to around 100,000 vehicles (Economist 2001).

There is sparse research focusing on VBTO systems and at this point in time there is no published analysis, algorithm or heuristic for dimensioning a VBTO system or guiding the design of the fulfilment logic.

6.3 Research agenda

The VBTO fulfilment model is the focus of the research. The overall goal is to understand and characterise its behaviour and performance to provide guidance for how such systems can be designed and managed effectively. VBTO is a system that is being adopted by automotive OEMs and hence there are identifiable beneficiaries of research.

The next four chapters present simulation and analytical studies that aim to build an understanding of the VBTO system and its behaviour and to provide the groundwork for such models.

The specific research aims are to:

- identify how the VBTO system differs from a conventional system (in which there is no access to the pipeline and customers are fulfilled from stock or by a BTO product);
- determine how a VBTO system can be dimensioned in terms of pipeline length in respect of fulfilment performance;
- identify the fundamental system design parameters that affect system behaviour and performance
- identify how the features of the system and characteristics of customers affect its performance.

To tackle this research agenda it is necessary to define and describe the features and mechanisms of a generic VBTO system (Chapter 7). Once this is done, approaches to modelling the system can be evaluated and selected (Chapter 7). Finally, models can then be developed and used for exploratory research (Chapter 8 to Chapter 11).

Chapter 7
Modelling the generic VBTO system

Abstract

The generic VBTO order fulfilment system consists of a stock of finished products and a pipeline of products that are planned for production or are in production. Reconfiguration flexibility is the ability to amend a product in the pipeline into a different specification. The producer has options for how to fulfil a customer, some of which are created by the system and others arising from customer differences. When cost of fulfilment is considered, the scope for developing complex fulfilment rules becomes evident. The performance measures and parameters to be studied are described.

Justification is given for why discrete event simulation is preferred as a research tool to system dynamics or agent based modelling methods. The structure and logic of the simulation model are described, as are the practicalities of the simulation experimentation, including the steps taken to assure validity of the results.

7.1 Description of the generic VBTO system

The VBTO order fulfilment system was introduced in the previous chapter. Here its generic features are described along with key concepts that are relevant to its operation and performance.

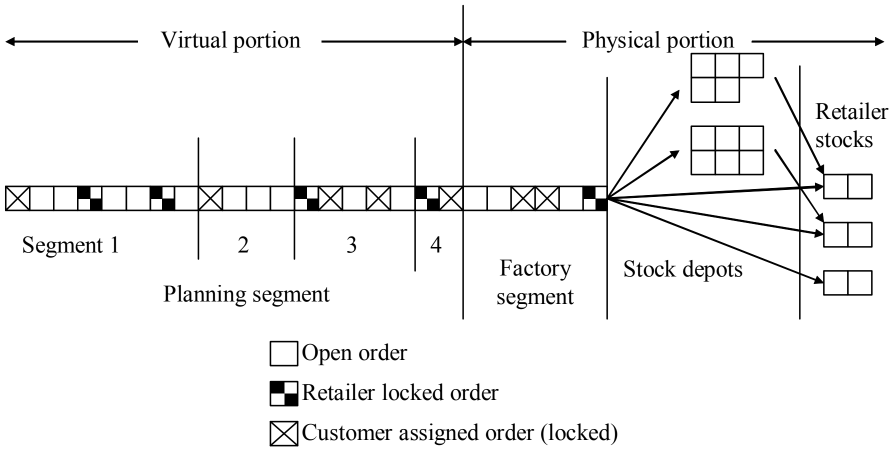
7.1.1 Structure and operation

In a VBTO system the order fulfilment pipeline can be conceived of as a series of *segments* (Figure 7:1). 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 more of 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. Retailers are vehicle dealerships.

Figure 7:1 Pipeline segments of a VBTO system



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;
  - being allocated to them while in the pipeline;
  - that is entered at the start of the pipeline i.e. a Built-to-Order (BTO) product.

7.1.2 Reconfiguration flexibility

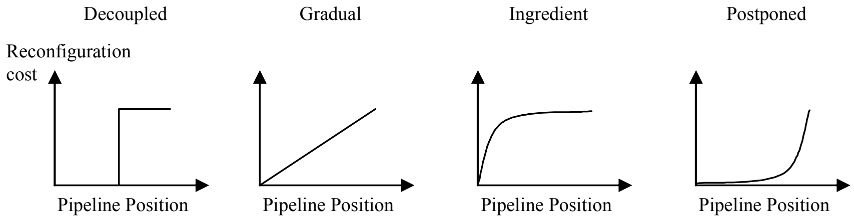
Reconfiguration is the process of changing a product's specification as it progresses along the pipeline. Depending on the point the product has reached the consequence of reconfiguring it could be no more than the future production plan being amended, or it could mean that components that have been 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 7:2):

- 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.

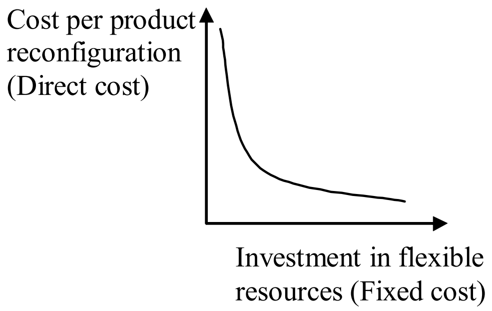
If a product is constructed from several features, their reconfiguration cost curves can be independent, especially if the supply resources necessary for their realisation are separate and independent. Consequently one feature can have a 'postponed' shape and another feature an 'ingredient' shape, while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

Figure 7:2 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 7:3). 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 7:3 Conceptual relationship between reconfiguration direct costs and investment in flexible resources



7.1.3 Strategies for fulfilling customers

The VBTO system creates options for how customer orders are fulfilled. The producer has scope to develop complex rules for searching and prioritising which products to offer to a customer. Some options are created by the system itself, such as allowing the producer to search stock first and then the pipeline, or vice –versa, but other options are created by differences between customers.

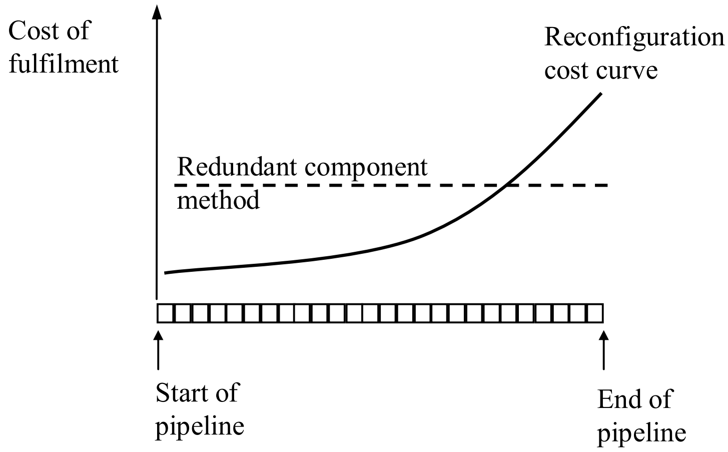
In making a purchase, customers may differ in the weights they give to delivery time, product specification and price. An alternative interpretation is that customers will differ in their *aversions to specification compromise and to waiting*. The operation of the VBTO system in this thesis addresses two of the customer's parameters – delivery time and product specification. Differences across customers in their aversions to delivery time compromise and specification compromise creates further options for how the producer uses the VBTO system to fulfil them. The producer can segment customers and apply different fulfilment search rules to each segment. A simple rule would be to prioritise products that are in stock or close to production for customers who want product as soon as possible.

Once attention is turned to the cost of fulfilment, the scope for creating complex search rules becomes evident. In their study of using vanilla boxes in the fulfilment process, Swaminathan and Tayur (1998) conjecture that it could be cost effective for the producer to supply the customer with a product that has superior grades of component(s) or even includes redundant components that the customer may not be made aware of, if the consequence of not doing so is to lose the sale. Their ideas prompt a set of five fulfilment strategies in regard to the specification of the product:

- Exact specification match: a product is found that is an exact fit with the specification requested by the customer;
- Specification compromise: the customer receives a different product to the one they have requested, of lower or equal grade;
- Specification substitution: the customer receives one or more superior features to those requested;
- Specification redundancy: the customer receives one or more additional features to those they have requested;
- Specification reconfiguration: an exact match is not found but a product is amended to the specification sought by the customer.

If an exact match is not available, 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 7:4.

Figure 7:4 Comparison of fulfilment methods in terms of cost



7.1.4 Primary performance metrics

The performance metrics of primary interest are:

- proportions of customers fulfilled via each of the three mechanisms – from stock, from the pipeline and by BTO;
- proportion of customers fulfilled by a reconfigured product;
- proportion of customers accepting a compromise / substitution;
- customer waiting time;
- cost of fulfilment;
- stock holding.

How these metrics are defined and captured is detailed in the simulation experiments in the following three chapters.

7.1.5 Factors studied in the research

The influences of the following factors are studied in this research:

- product variety, in terms of the number of unique variants in the product range;
- pipeline length;
- rules for feeding products into the pipeline;
- reconfiguration flexibility and cost of reconfguration;
- customer willingness to compromise;
- customer aversion to waiting;
- fulfilment policies, in regard to the rules used to search stock and pipeline on behalf of a customer.

Throughout the investigations the system is studied without feedback loops, i.e. there is no adjustment of the feed into the pipeline in response to customer orders or the status of the pipeline and stock. This is done deliberately to allow the fundamental behaviour of the system to be observed. The development of such control logic will benefit from this understanding and is a task for future research.

7.2 Modelling approach

Two techniques are used to study the VBTO system – discrete event simulation and Markov modelling. Computer based simulation allows the internal complexity of a system to be modelled and its behaviour studied. The simulation study is presented in chapters 8,9 and 10.

VBTO, which has interacting stochastic processes, qualifies as a complex system and is a challenging system to model using analytical methods. The attempt to represent the VBTO system as a Markov process (Chapter 11) has used the knowledge obtained from the preceding simulation studies and would have been difficult to construct and validate without the simulation insights. The Markov study is presented ion Chapter 11.

A research approach that involves trials on a real-world system is not an option, hence the selection of simulation as the primary method. It is for circumstances such as these that simulation is advocated as a research tool (Law & Kelton 2000, Pidd 1998, Ravindran *et al* 1987). Simulation models are an abstraction of the real-world, which is a source of inaccuracy but also an opportunity as it allows complexity to be removed and added in controlled stages, enabling cause and effect relationships to be identified and evaluated. Other potential weaknesses of simulation are that it is time-consuming, difficult to validate and can get out of hand, with the temptation to add features to the model. In the context of a doctoral project the first is not a bar, the second has been addressed during the research, and a keen eye on focus has held back the temptation to over elaborate.

There is considerable flexibility in how to undertake a simulation based research study. One option is to construct a simulation model incorporating all factors of the system being studied and then use a designed experiment to gauge the sensitivity of performance to these factors, such as using a fractional- or full-factorial design with ANOVA. This approach has not been employed in this set of studies. Instead, the VBTO system has been examined at different levels of abstraction. In the simplest case it has been abstracted to two simple sequences of random numbers, one to represent the pipeline of products and the other the customers. The investigation has then progressed by increasing the complexity of the model in stages and examining the changes in behaviour that result. The main reason for taking this route is that it is not only the strength of effect of a factor that is of interest but how and why a factor alters the behaviour of the system. A further reason for this exploratory approach is that no quantitative or analytical studies of VBTO systems have been reported in the literature. Understanding the fundamental behaviour of such systems is important at this stage in their development. The findings regarding stock levels, presented in section 8.4.1.2 provide, perhaps, the strongest support for the approach.

7.2.1 Simulation

7.2.1.1 Choice of simulation method

Three types of simulation can be used in the study of order fulfilment systems – discrete-event, continuous and agent based.

In a discrete-event simulation a system is modelled as a sequence of distinct states, with the system variables changing instantly at each point in time that a new state is entered. In regard to the simulation of production and supply systems it has been the default simulation method. Such models consist typically of sequences of processes and queues, with orders, materials or products moving between them according to some control logic.

The fundamental difference between continuous and discrete-event simulation is that in a continuous simulation the variables change continuously with respect to time. The constituents of a model resemble reservoirs, pipes and valves with the logic of the model controlling time lags and rates of flow within the system. Jay Forrester (1961) showed how the dynamic behaviour of industrial systems could be revealed through continuous simulation and it is an approach that is suited to modelling the dynamics of business processes (Sterman 1999).

Agent based simulation was developed for the study of biological systems. An important difference between it and the previous methods is that the modeller defines only how each type of agent interacts with other types. Overall system behaviour becomes apparent only when the simulation is run and the agents follow their rules. Swaminathan *et al* (1998) demonstrate how a supply system – with manufactures, distributor and retailers – can be simulated as an agent based model.

These approaches to simulation can be combined and it is not the case that a simulation package restricts the analyst to one approach (Law & Kelton 2000). In their demonstration of agent based simulation, Swaminathan *et al* (1998) comment that the approach could be implemented in discrete-event simulation languages.

The VBTO fulfilment model fits into the production system paradigm, with the pipeline resembling the queue in front of the final assembly process. The state of the system changes at fixed intervals, either at the arrival of a customer, at the entry of a product, or when product moves in discrete stages through the process. These aspects, and the fact that there is no need to model any variable as continuous, makes discrete-event simulation the natural choice.

7.2.1.2 Selection of simulation package

There are many dedicated discrete event simulation packages and at no time was the option of creating a bespoke simulation tool entertained. Two simulation packages were considered – ARENA[13] and GPSS[14]. In ARENA a model is constructed within a graphical interface by connecting basic or advanced modules from a library. The package generates SIMAN code which can be edited (Kelton *et al* 1998). GPSS, which stands for General Purpose Systems Simulator, is a simulation language developed for IBM in the early 1960s (Stahl 2001).

Early work in the research established that GPSS was well suited to modelling the VBTO system:

- Once the basic structure of the VBTO system had been coded in GPSS, the length of pipeline and variety of products could be controlled by variables, whereas it was found that the basic structure of the ARENA model had to be modified;
- GPSS was equipped with several built-in functions (known as *blocks* in GPSS) that made it straightforward to search the pipeline of products for the closest match to a customer's specification. The equivalent functions were not in SIMAN and ARENA was abandoned before a solution was developed.

7.2.1.3 Stages of the Simulation

The simulation studies have followed a standard process, similar in outline to that described in Law & Kelton (2000);

- definition of the system: the overall VBTO system has been described in the previous chapter, and in each stage of the study the factors under investigation are highlighted;
- coding and verification of the model: GPSS lacks a graphical interface hence verification relied on review of intermediate and output data. An example is given in section 8.3.1.1 (page 68).
- defining and performing experiments: the focus of the research has been to understand VBTO systems behaviour and relationships between factors. In many cases the approach has been to study the impact of a factor, or the interaction of factors, across a range of scenarios e.g. from low to high product variety.
- analysing results: interpretation of graphical plots has been used extensively.

7.2.1.4 Simulation model

The simulation is coded in GPSS, a language in which *transactions* move between *blocks*, and carry information in *attributes*. In the VBTO model there are two sequences of transactions, one representing products and the other customers. The set of blocks for these two sequences are kept separate in the model, and the customers and products interact through information flows only. A schematic of the model is shown in Figure 7:5.

Details of the simulation and how the search mechanism is implemented are given below. The variables that need to be defined for each run are highlighted in *italics*.

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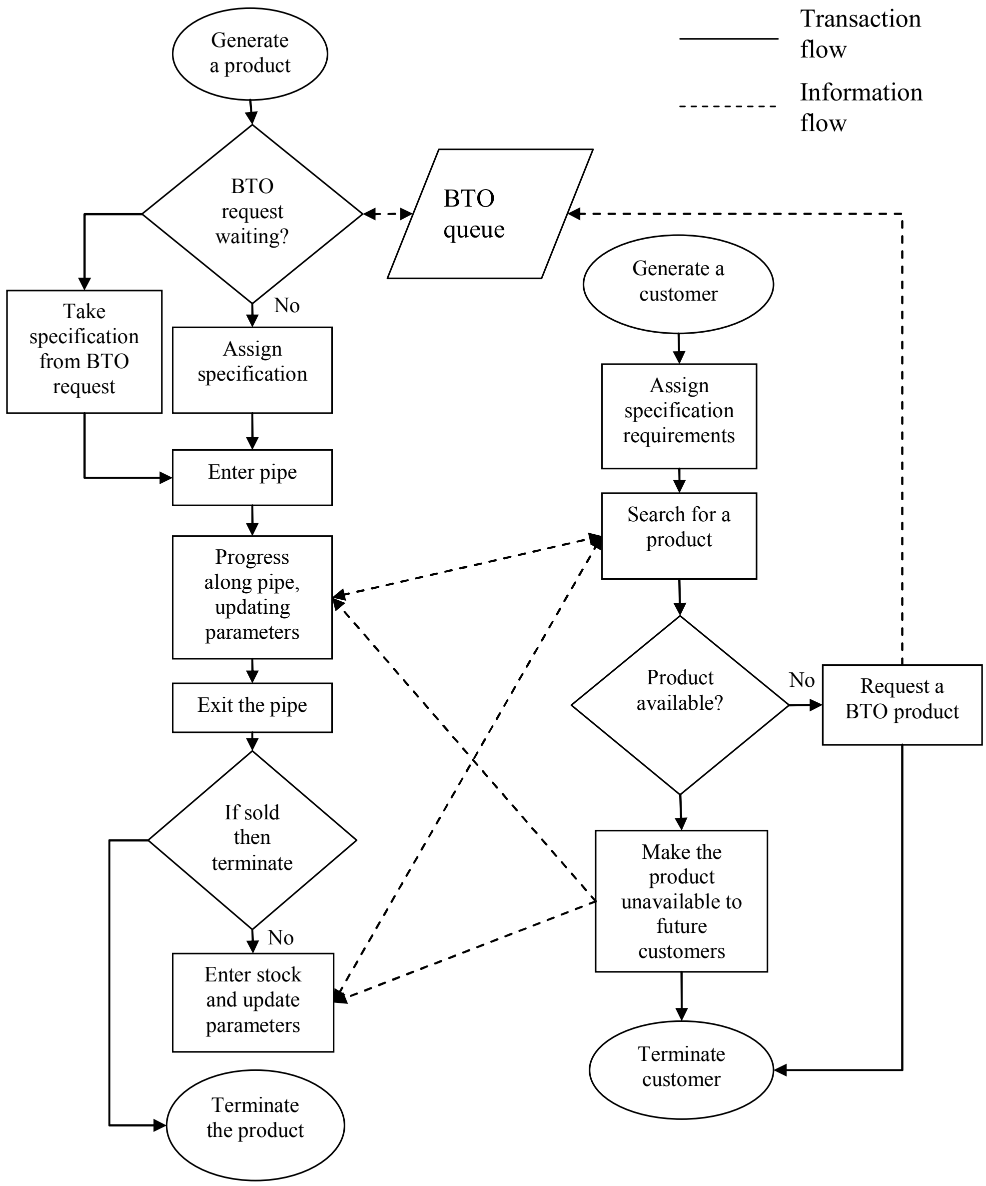
[13] ARENA, Rockwell software, www.arenasimulation.com

[14] GPSS, Minuteman Software, www.minutemansoftware.com

Figure 7:5 Schematic of transaction and information flows in the model



Product flow

Products are created at a *production rate.* Before each enters the pipeline it checks the BTO queue, and if there is a BTO request waiting, the product assumes the identify of the BTO order, has its sold attribute set to 'true' and enters the pipeline. If the BTO queue is empty, before entering the pipeline the product is assigned a specification according to the *product specification rule* and its data attributes are initialised, including having its sold attribute set to 'false'. The data attributes carry information about the product, such as when the product was created, its specification, which variants it can be reconfigured into, how much it would cost to reconfigure it into each of these variants, which variants it can be compromised for.

In Chapter 8 a product is specified by its variant number, so if the product range is 6, a product will be given the specification of #1, #2, #3, #4, #5 or #6. In Chapter 9 and Chapter 10 a product is specified as a combination of four features, and each feature has a number of options (the approach is explained in the chapters).

Each product carries a few core attribute values (such as for its creation time, and its specification) and also as many attributes as there are variants in the product range. Hence, if the simulation is analysing product variety of 4, each product will carry 4 additional attributes as well as the core attributes. If the product range is 4096, each product will carry 4096 additional attributes. The reason for this is to do with the search method and is explained below.

The product progresses along the pipeline in discrete steps, at the rate of one step per time period. Some data attributes are updated at each step, such as the cost of reconfiguration which can be dependent on location.

If the product is allocated to a customer while it is in the pipeline, it has its sold attribute set to 'true' but it remains in the pipeline. When it exits the pipeline, this attribute is inspected and all sold products are diverted to a termination block.

On close study of the schematic it can be seen that products that reach stock never leave it. Once sold they are made invisible to later customers but they are not sent to a TERMINATE block. To have them terminated would require them to be inspected and routed by additional blocks but it is judged that the build up of transactions in the model slows the simulation less than would the additional blocks.

Customer flow

Customers are created after an *initial delay* and at a *customer creation rate*. Each customer is assigned a specification according to the *customer specification rule*. Each customer is assigned a type, according to the *customer typing rule*. Each customer type has rules set for whether it is prepared to compromise and by how much (its *compromise rules*). The customer then searches for a product and the mechanics of this process are described below. If no suitable product is found a BTO request is generated if the *BTO switch* is 'on'. If it is 'off' then this customer is registered as a lost sale. Whether the customer is fulfilled or lost it then triggers the updating of the simulation statistics (proportion fulfilled by each mechanism, waiting time, proportion compromising, etc) before being terminated.

How customers search for a product

Two function blocks in GPSS (the ALTER and SCAN blocks) allow a transaction to search and read back information from the attributes of a transaction in a *group,* and these blocks have been configured to search for the best product for a customer.

All products that are available to customers are joined to the available group. Products that fulfil a BTO request do not join this group and when a product is sold it is removed from the group. When a search is made of the available group, the search is looking for the product that most closely matches the needs of the customer.

When a customer searches for the best product of a particular specification, say variant #5, all of the products in the available group are inspected. Specifically, the attribute #5 of each product is examined and the product with the lowest value in this attribute is selected. This is illustrated in Table 7:1, which shows the first six products available in the pipeline. Product no.61 is the oldest product and hence is the product furthest downstream. Some products have been sold and therefore do not appear in the available group (e.g. product no. 64). The attributes of each product indicate how much the product's specification differs from the attribute number. For example, product no. 61 has a specification of 3, hence its #5 attribute contains the number 2.

There are two products in the available group that match the customer's specification – no's 63 and 68. By default GPSS selects the oldest transaction, i.e. product no. 63. It is therefore straightforward to implement a FIFO search in GPSS. To implement a LIFO search a decrementing value is appended to each attribute, as illustrated in Table 7:2, which gets product no. 68 selected.

Table 7:1 Search illustration: FIFO search (later referred to as a backwards search)

Product no.	61	62	63	65	68	70
Specification	3	2	5	1	5	4
Attribute #						
1	2	1	4	0	4	3
2	1	0	3	1	3	2
3	0	1	2	2	2	1
4	1	2	1	3	1	0
5	2	3	**0**	4	0	1
6	3	4	1	5	1	2
7	4	5	2	6	2	3
8	5	6	3	7	3	4

Table 7:2 Search illustration: LIFO search (later referred to as a forwards search)

Product no.	61	62	63	65	68	70
Specification	3	2	5	1	5	4
Attribute #						
1	2.99	1.98	4.97	0.95	4.92	3.90
2	1.99	0.98	3.97	1.95	3.92	2.90
3	0.99	1.98	2.97	2.95	2.92	1.90
4	1.99	2.98	1.97	3.95	1.92	0.90
5	2.99	3.98	0.97	4.95	**0.92**	1.90
6	3.99	4.98	1.97	5.95	1.92	2.90
7	4.99	5.98	2.97	6.95	2.92	3.90
8	5.99	6.98	3.97	7.95	3.92	4.90

The approach described above can be adapted to increase the sophistication of the search. For example, the difference can be made negative or positive, or a rule can be used that tests if the difference is greater than a threshold and if so sets the attribute to a value of, say, 10,000 to indicate the product cannot be reconfigured into the customer's target specification. For each simulation experiment a number of *search rule switches* are set to create the required search method.

User defined simulation model parameters

The parameters listed below control each simulation experiment. Details are given below, and relevant information is also given in later chapters:

- *pipeline length*: this is the length of the pipeline in terms of the number of products it holds.
- *production rate*: in all simulations reported in the research the fixed production rate of 1 product per time period has been used.
- *initial delay*: this is the delay between the creation of the first product and the arrival of the first customer. Throughout the research the initial delay is set to be equal to the length of the pipeline. In other words, the pipeline is filled before the first customer arrives
- *customer creation rate*: in all simulations reported in the research the fixed arrival rate of 1 customer per time period has been used.

- *product range*: the number of products in the range. When the product is modelled as having a modular architecture (as is the case in Chapter 9 and Chapter 10) the number of features and the number of options per feature must be set.
- *product specification rule*: in all cases this is either a uniform or beta[15] random function
- customer specification rule: in all cases this is either a uniform or beta random function
- *customer typing rule*: if there are different customer types, the number of types is set and the rule for assigning a customer to a type is set. This is either a uniform random function or a user defined discrete random function
- *reconfiguration flexibility*: this governs whether a product can be reconfigured and the extent to which it can be. When the product is modelled as having a modular architecture, the flexibility of each feature is set independently.
- *reconfiguration cost function*: the parameters of the cost curve are set (see Chapter 10).
- *customer compromise*: this defines the extent to which a customer will compromise from their target specification.
- *BTO switch*: when on, the simulation will generate a BTO request when no suitable product can be found. When off, the customer will be lost in this circumstance.
- *stock switch*: When on the products leaving the pipeline will enter stock. When off, unsold products are removed from the simulation.
- *search switches*: as described above there are a number of switches that control how the search is performed.

7.2.1.5 Simulation practice

For the findings from a simulation study to be valid, requires attention be given to statistical matters. Although the analysis of simulation data relies on the familiar principles of statistical sampling, care needs to be taken in how randomness is handled in the simulation and how data is sampled in order to avoid bias. Transient periods and autocorrelation are two issues which can reduce the validity of simulation results (Law & Kelton 2000, Pidd 1992). In the simulation studies reported in the following chapters, the following practices have been applied (Law & Kelton 2000, Pidd 1992):

- each feature in the model that requires an independent and identically distributed sequence of numbers has been identified and allocated to random number streams so as to ensure independence;
- the variance reduction method of common random numbers has been used;
- the system has been analysed as a non-terminating system. Consequently a warm-up period has been allowed for, with the data from this period discarded;
- data samples from the simulation have been collected using the method of *batch means*. In this approach a long run is divided into a series of sub-runs, thereby having one warm-up period only. The statistics from 9 batches (replications) are combined to calculate the performance metrics for each set of experimental conditions.

Further technical aspects of the simulations are described in Appendix E.

7.2.2 Analytical modelling

Chapter 11 describes how a Markov model of the VBTO system has been developed and tested. Production systems with stochastic processes can be suited to being modelled as a Markov process (Jensen & Bard 2003). Although the validity of Markov modelling is limited to certain statistical conditions, it could open a route to developing an analytical model that could give greater precision and faster analysis than discrete-event simulations.

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[15] The Beta distribution is used due to its the shapes of distributions it can be manipulated into and that it has fixed lower and upper bounds

Chapter 8
Fundamental behaviour of the VBTO fulfilment model

Abstract

Simulation is used to investigate and profile the fundamental behaviour of the basic VBTO system. The chapter examines how factors including product variety, pipeline length, demand pattern, and customer differences affect operational performance, in particular the mechanism by which customers are fulfilled. The results show how variety/pipeline length ratio, direction of search, the level of reconfiguration flexibility and customer tolerance to specification compromise influence the performance metrics– likelihood of an order being fulfilled, waiting time and stock holding.

8.1 Introduction

In this chapter the VBTO system is studied to build an understanding of its fundamental behaviours and performance.

The ability to search the pipeline and allocate a product from any point along the pipeline distinguishes VBTO from other fulfilment systems that have one or more fixed decoupling points. How this difference in system design affects fulfilment performance is of great interest. In this chapter the VBTO system with its three fulfilment mechanisms – fulfilment from stock, from the pipeline and fulfilment by means of BTO – is compared to the conventional system that has just two mechanisms – fulfilment from stock or fulfilment by BTO.

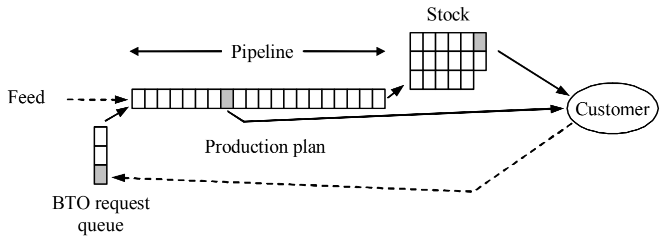
Before studying the behaviour of the three mechanisms, the first part of this chapter studies a simplified model where the system just allows the pipeline fulfilment mechanism. The properties of this system help to illustrate and explain the later more complex systems. The first issue examined is the impact of product variety on fill rate and it is shown that fulfilment is affected by how the pipeline is searched and that there are consistent relationships between fulfilment and system parameters. Of interest is how this relationship is altered by endogenous and exogenous factors, in particular the ability to reconfigure products and the shape of the demand distribution.

8.2 Approach

8.2.1 VBTO Model

In this chapter the VBTO system is modelled as a system with three segments: a stock of unsold products, a production plan which is the sequence of products to be or being manufactured (referred to as the pipeline) and a BTO queue (Figure 8:1). In the study the production rate and customer arrival rate are constant and equal. Products enter the pipeline and customers arrive at a rate of one per period. Once products have entered the pipeline they cannot be re-sequenced. The sequence of products fed into the pipeline is random and uncorrelated. When a customer arrives, they have a preferred variant from the range in mind and a product that matches their preference is sought. The customer can be fulfilled from any of the segments. When a product is allocated to a customer it is made unavailable to subsequent customers. BTO requests are fed in at the start of the pipeline at the earliest opportunity (therefore, if the BTO request queue is empty an unallocated product is fed into the pipeline).

Figure 8:1 Schematic of the VBTO order fulfilment system showing three fulfilment mechanisms



8.2.1.1 *Representation of product variety*

The product range is represented as a set of discrete variants, with each variant assigned a unique number. For example, if the product range has five variants, they are identified as 1, 2, 3, 4 & 5. It is assumed that, from a customer perspective, the degree of difference between two variants is proportional to the absolute difference between the variant numbers. Therefore, to a customer, the difference between a variant type 8 and variant type 4 is twice as great as between a variant type 7 and type 9.

8.2.1.2 *Performance Metrics*

The performance metrics of primary interest in this chapter are

- the proportion of customers fulfilled by each mechanism,
- the level of stock holding and
- waiting time.

It should be noted that customers fulfilled from stock are modelled as being fulfilled instantly.

8.2.2 *Study phases*

In order to gain clear insights into the key aspects of VBTO system behaviour and performance, the study is divided into two phases. The first phase studies the pipeline segment of the VBTO system in isolation and examines its behaviour for different levels of variety and different distributions of variety. In the second phase the full VBTO system is studied with particular attention given to the impact of reconfiguration flexibility and customer behaviour.

8.3 Phase 1: Study of a 'Pipeline only' system

This section focuses on the pipeline in isolation. Products enter the pipeline and, if they are unsold by the time they reach the end, they are removed from the system and cannot be accessed by customers. If there is no matching product in the pipeline then the customer is lost (i.e. no BTO request is made).

Three situations are studied: uniform variety distributions; non-uniform variety distributions; and reconfiguration flexibility.

8.3.1 *Uniform variety distributions*

In this study both the distribution of variety demanded by customers and the distribution variety fed into the pipeline are modelled as uniform random distributions. Hence, all variants have equal likelihood of being fed into the pipeline and of being ordered by a customer. The aim is to quantify the effect of search direction on the likelihood of finding a match in the pipeline for a customer. The pipeline can be searched backwards or forwards (which are equivalent to FIFO and LIFO logic).

8.3.1.1 *Observations*

The results of a pipeline of length 128 for a range of variety levels are given in Figure 8:2, which has a logarithmic variety scale. For medium to low variety levels, it shows that a lower proportion of customers are fulfilled when a forward (LIFO) search is used compared to a backward (FIFO) search. The difference disappears at very high variety levels.

The pattern of fulfilment is the same for both search methods. At low variety there is a high likelihood of a match in the pipeline, and as variety rises the match likelihood drops. The change in variety level between a ~90% and ~10% fulfilment likelihood is around 2 orders of magnitude.

The difference between the two search methods can be explained with the aid of Figure 8:3. If two products in the pipeline match the customer's order, a backward search policy will allocate the product that is farthest downstream, as opposed to the product that is farthest upstream that is allocated by the forward search policy. The allocated product remains in the pipeline until it reaches the end and, until it leaves, it depletes the total number of potential products available to subsequent customers. The residence time in the pipeline of products allocated through a backward search is therefore less than in a forward search. Hence, compared to the forward search, the backward search leads to a smaller reduction in the available number of products. At a low or medium variety level there is a significant likelihood of two or more suitable products being in the pipeline, but as can be observed in Figure 8:2, the difference between the forward and backward search policies diminishes as variety increases. This is as expected since the likelihood of there being two or more matching products in the pipeline also declines as variety increases.

Figure 8:2 Probability of an exact match for each search method (Pipeline 128)

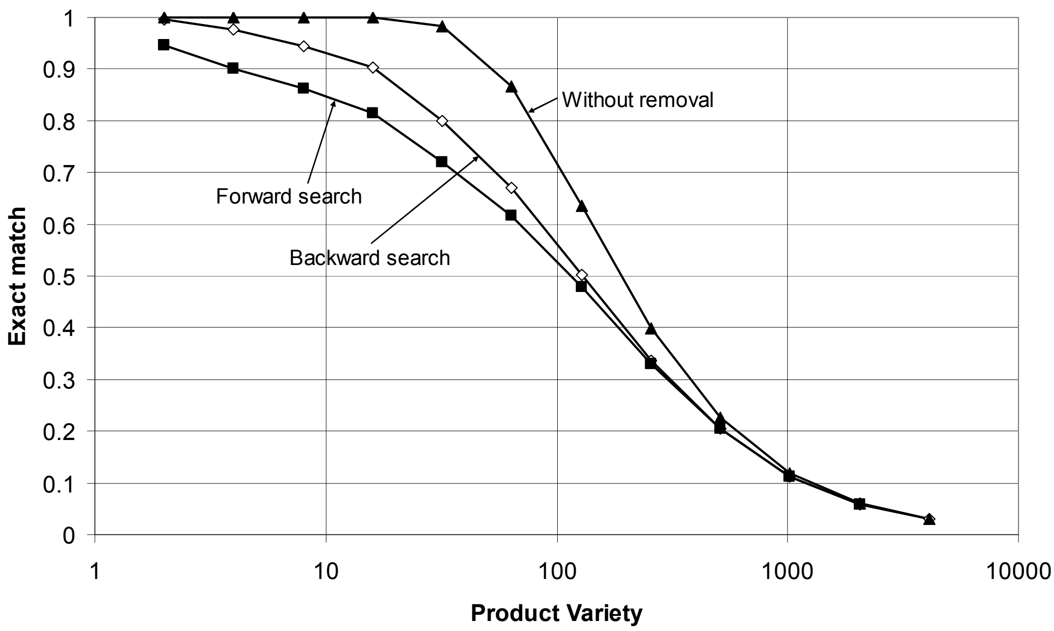
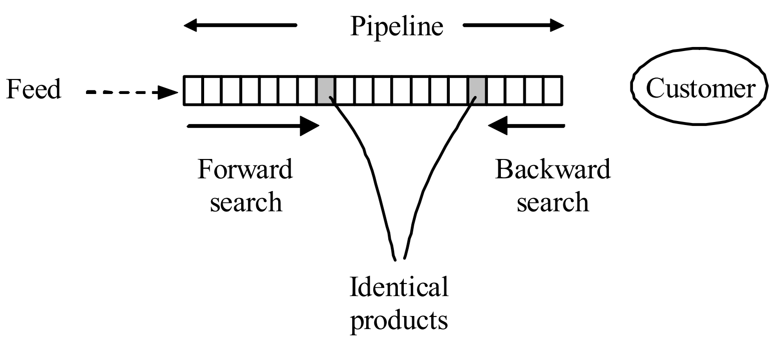


Figure 8:3 Search directions

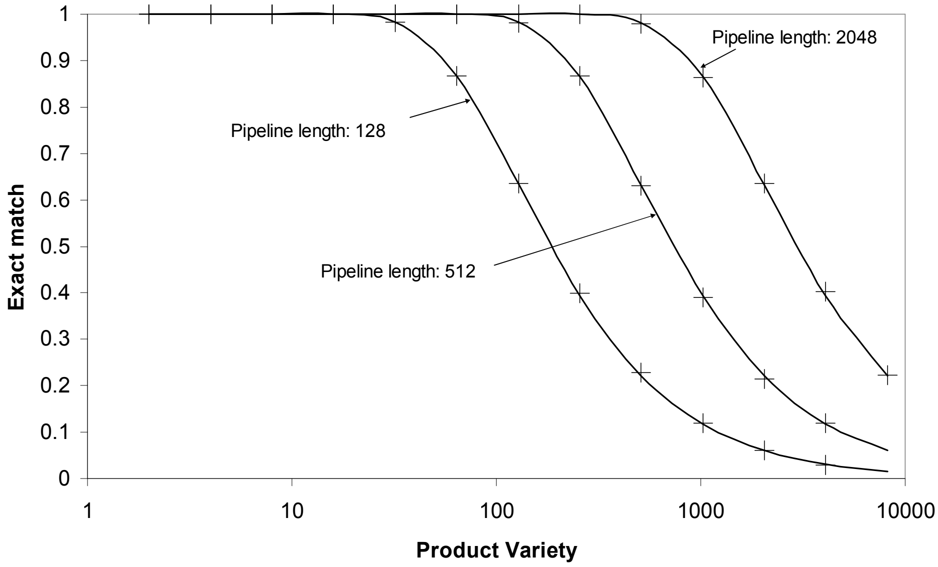


Comparison with a Binomial model

Figure 8:2 includes a third curve labelled 'without removal' that was generated by searching for a matching product in the pipeline but then <u>leaving</u> it available to subsequent customers. This is equivalent to a 'with replacement' selection process and means that every customer has a full pipeline available to them. Given the nature of the variety distributions for the feed into the pipeline and for the sequence of customer orders (with both being a random sequence from uniform distributions) a binomial model should give the same results as the 'without removal' case, and this is found to be true (Figure 8:4). Three pipeline lengths have been simulated for a range of variety conditions and compared to the binomial model (with '+' points plotted on the graph). This result validates the basic simulation model and logic used.

The probabilistic properties of the pipeline are studied in Chapter 11 ' Modelling VBTO systems as Markov chains' (starting on page 163).

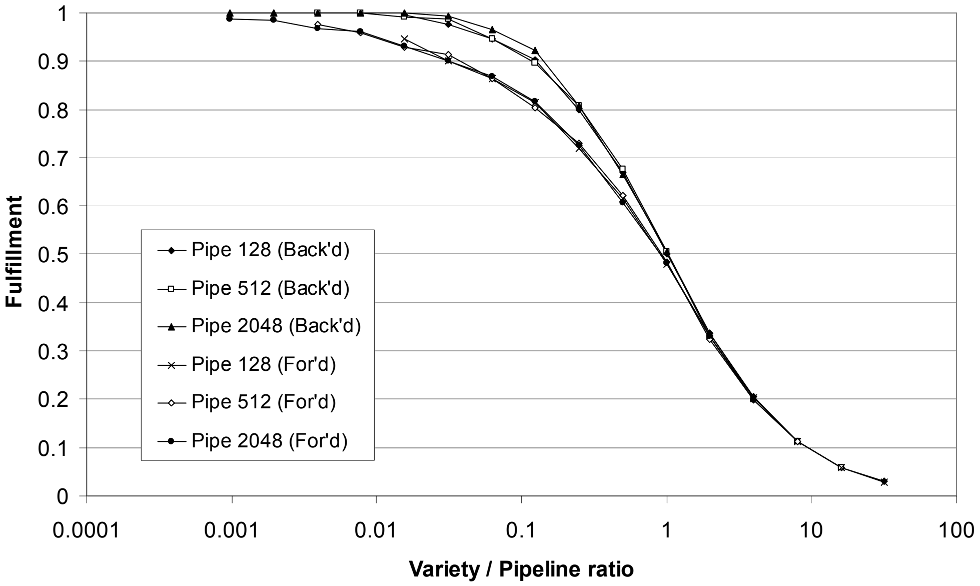
Figure 8:4 Comparison of the Binomial model and 'Without removal' simulations for three pipeline lengths (Binomial points indicated by '+')



Variety/Pipeline Ratio

An important and fundamental finding is that a consistent pattern is found when other pipeline lengths are simulated, and the fulfilment likelihood plotted against the ratio of variety to pipeline length. In Figure 8:5 pipelines of 3 lengths have been simulated at 12 variety levels, from 2 to 4096, using both forward and backward search methods. This ratio will be shown to influence the behaviour of VBTO systems fundamentally.

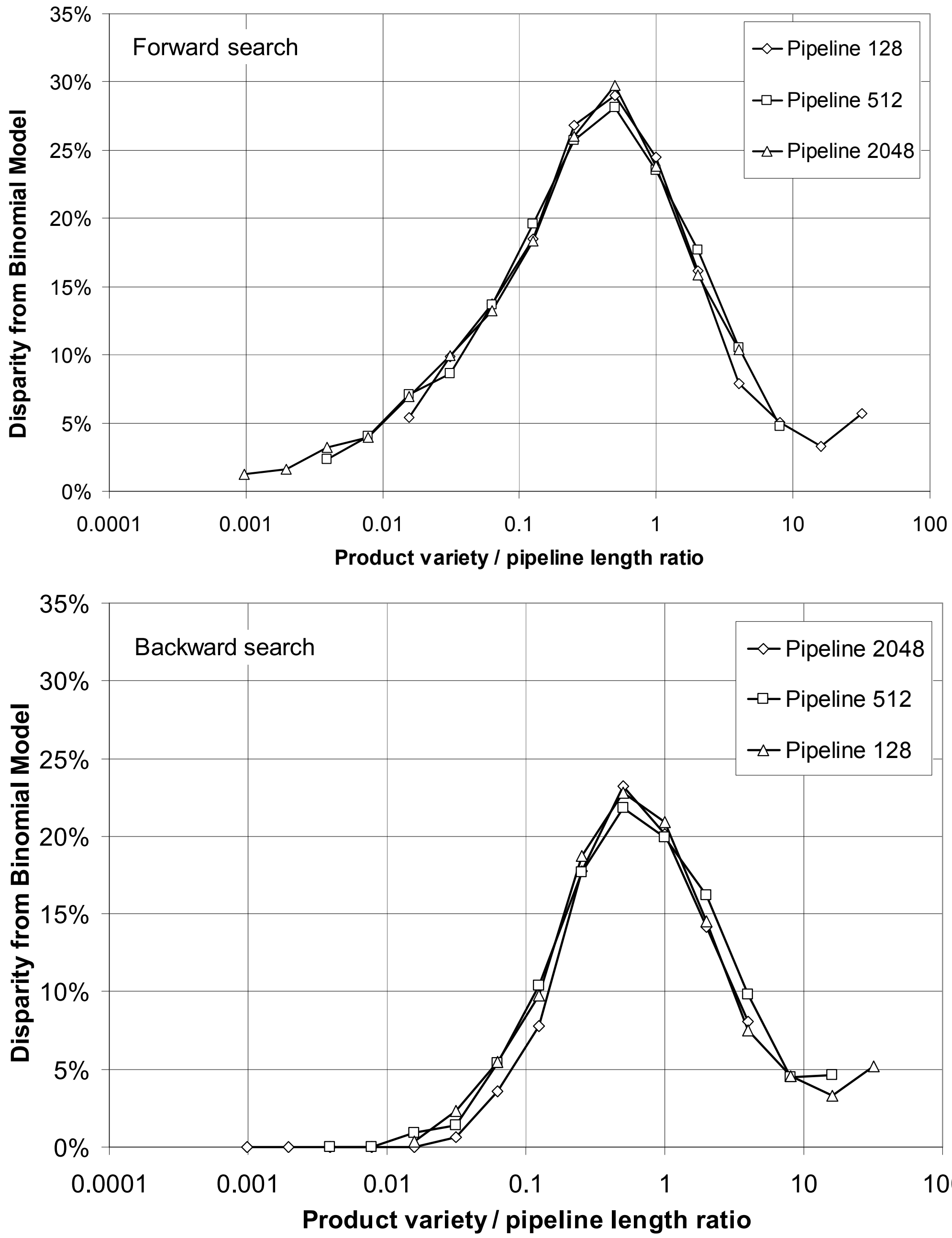
Figure 8:5 Combined plot of backward and forward fulfilment vs. Variety / Pipeline ratio for 3 pipeline lengths



An inference from this finding is that the disparity between the binomial model and the two search policies is predictable, as shown in Figure 8:6. These plots allow the performance of the pipeline-only system to be gauged by reference to these curves after a simple and quick Binomial calculation. At very low and very high ratios the difference is negligible but is more significant at ratios between 0.02 and 10.

In each graph in Figure 8:6 the curves turn up at the rightmost end. This is judged to be due to small numerical errors resulting from simulation experimentation. As the variety/pipeline ratio increases the likelihood of a match in the pipeline tends to zero. Consequently, even a small error in absolute terms appears to be sizeable when converted into a percentage difference.

Figure 8:6 Disparity from the binomial model for forward and backward searches



8.3.2 Non-uniform variety distributions

The charts above have been generated using sequences sampled from uniform random distributions and a key question is whether the findings hold when the distribution is skewed, which may be a more typical situation faced by producers. Here non-uniform distributions are used for both produced variety i.e. pipeline feed, and customer demanded variety.

To enable the effect of increasing skew to be compared to the results from the uniform distribution in section 8.3.1, the Beta distribution was chosen due to it having defined upper and lower values and two parameters that allow its shape to be manipulated. For a product range of 32, six levels of increasing skew are modelled, with the largest representing a 90/10 ratio (i.e. 10% of products account for 90% of demand) and the lowest representing a 60/50 ratio (i.e. half of the products account for 60% of demand). Figure 8:7 and Figure 8:8 show two of the distributions modelled and the details of the six distributions are given in Table 8:1.

The customer demanded variety and produced variety are skewed in the same direction and to the same degree and a backward search is used.

Table 8:1 Beta distribution shape factors (α & β), skew and summary ratio

Distribution ref	Beta			
	α	β	Skew[16]	Summary
0	1	1	0	Uniform
1	1	1.31	0.23	60/50
2	1	1.68	0.43	60/40
3	1	1.91	0.53	50/30
4	1	3.3	0.93	70/30
5	1	7.5	1.39	80/20
6	1	23	1.76	90/10

Figure 8:7 Beta distribution equivalent to '60/50' ratio (Product range 32, shape factors α=1, β=1.31)

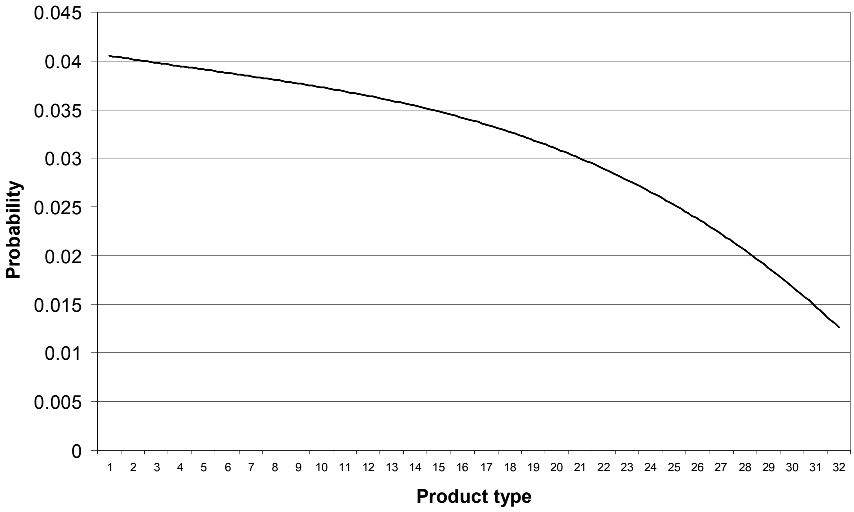
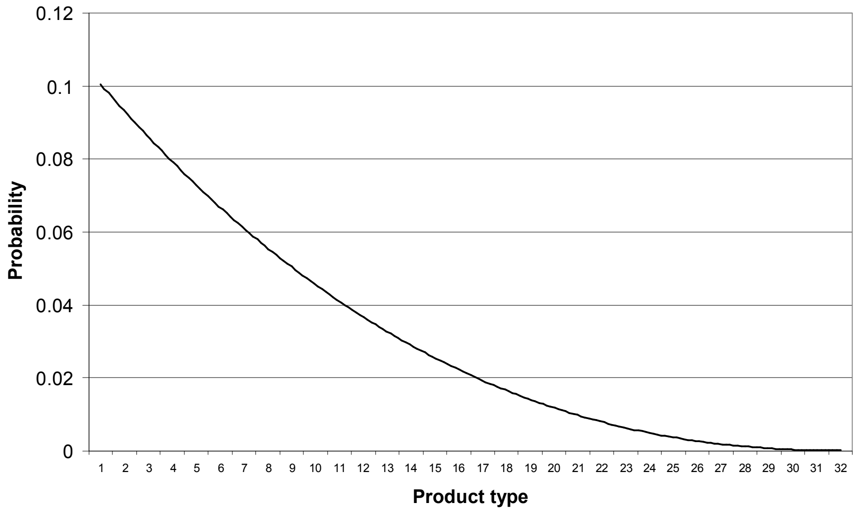


Figure 8:8 Beta distribution equivalent to '70/30' ratio (Product range 32, shape factors α=1, β=3.3)



[16] Skewness = $(2(\beta-\alpha)/(2+\alpha+\beta))\sqrt{((1+\alpha+\beta)/\alpha\,\beta)}$
Source: http://mathworld.wolfram.com/Skewness.html

8.3.2.1 *Observations*

The impact on the proportion of customers fulfilled is shown in Figure 8:9. At the lower skew levels the proportion of customers fulfilled increases slightly over the uniform case. At higher skew levels the difference becomes pronounced as the variety/pipeline ratio increases. The difference is greatest when the variety / pipeline ratio is between 1 and 4 (Figure 8:10). When the distribution is skewed to 90/10, the proportion of customers finding a match in the pipeline increases from 21% to 75% at the ratio of 4. By increasing skew simultaneously in pipeline feed and in customer demand we are effectively reducing variety, hence the variety/ pipeline ratio is reducing and higher level of fulfilment is expected.

Figure 8:9 Proportion of customers fulfilled at different pipeline lengths for 6 skew levels (variety of 32)

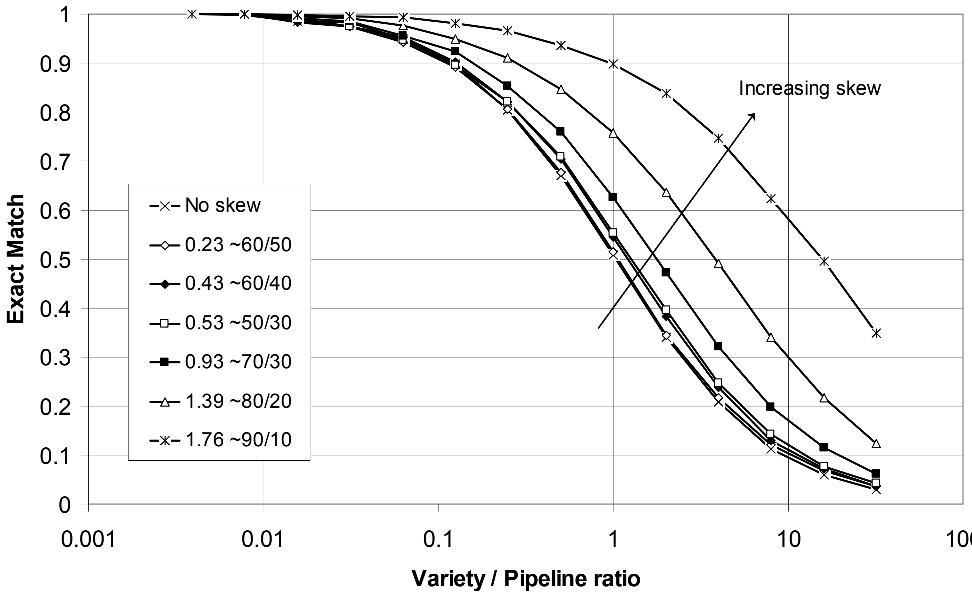
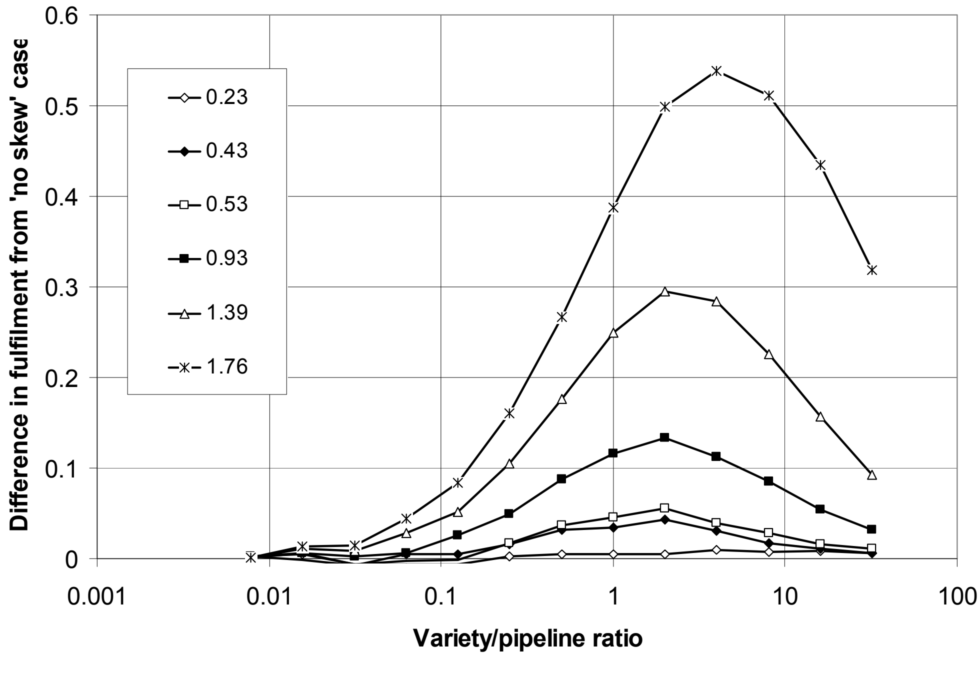


Figure 8:10 Difference in fulfilment between 6 skew levels and zero skew (variety of 32)

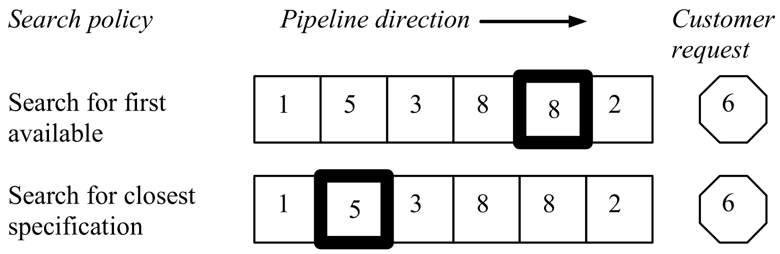


8.3.3 *Reconfiguration flexibility*

In this analysis products in the pipeline can be reconfigured and the effect of increasing reconfiguration flexibility is studied. Two-way reconfiguration flexibility allows a product to be altered upwards or downwards. For example, if the pipeline has a reconfiguration flexibility of 4, a product that enters the pipeline with the specification '37' can be reconfigured into any of 33, 34, 35, 36, 38, 39, 40 or 41. If the reconfiguration flexibility is restricted to one-way, the '37' can be reconfigured into 38, 39, 40, or 41 (this is labelled as one-way upward reconfiguration flexibility).

When searching the pipeline on behalf of a customer two methods are possible. One is to minimise the amount of reconfiguration by finding the product with the closest specification - a rule that gives preference to an exact match. An alternative rule is to search the pipeline for the first available product that can be reconfigured. These are illustrated in Figure 8:11 for a backwards search.

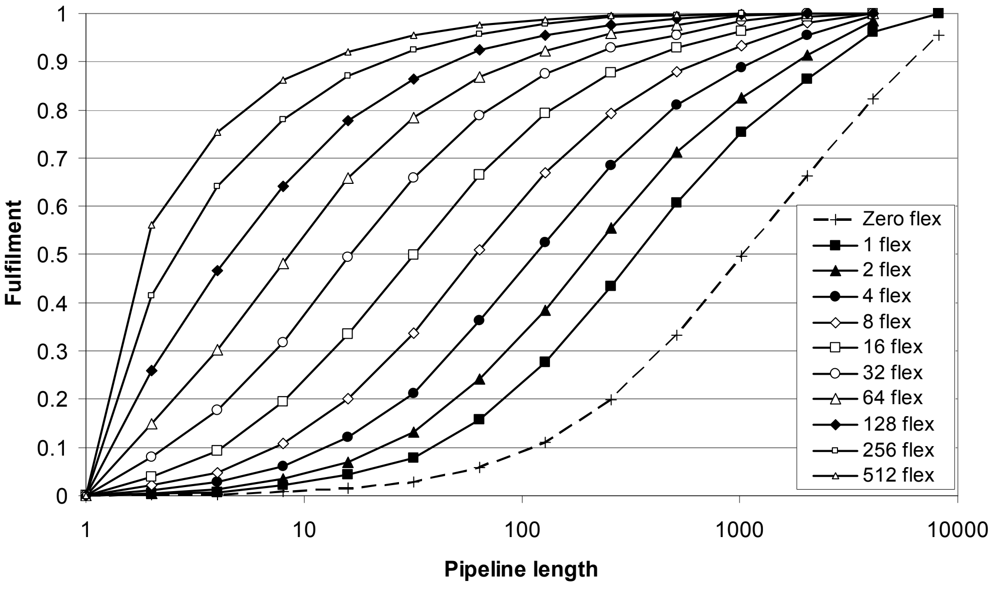
Figure 8:11 Comparison of two search policies in a pipeline with reconfiguration flexibility +/-2, *backwards* search



8.3.3.1 *Searching for the closest specification*

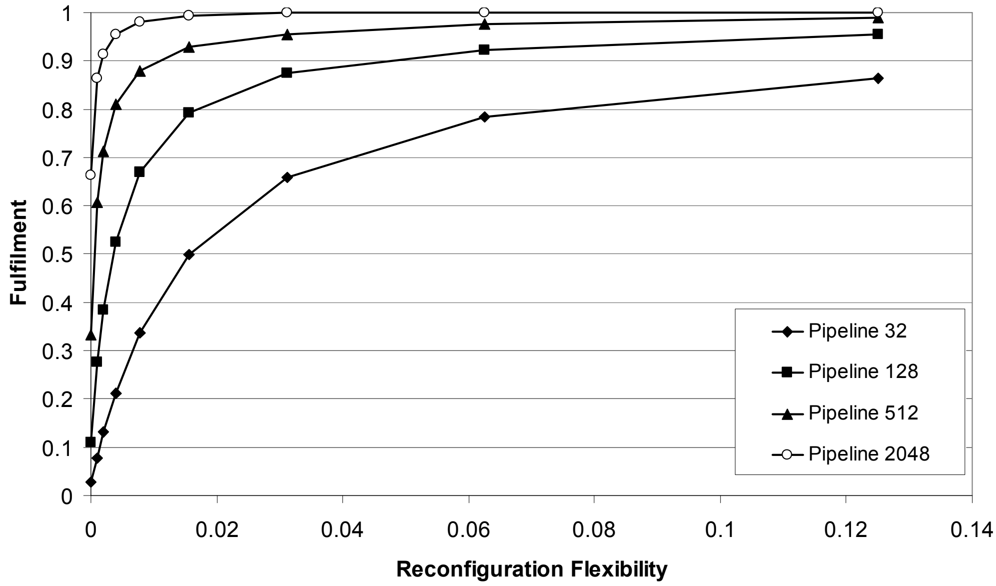
The effect of reconfiguration flexibility is illustrated in Figure 8:12. The product variety is 1024 (selected as it illustrates the pattern of behaviour over pipeline lengths 2 to 8192) and flexibility is increased in steps from +/-1 up to +/-512.

Figure 8:12 Effect on proportion of orders fulfilled of increasing reconfiguration flexibility (Two-way flexibility, Variety 1024)



An alternative presentation is in Figure 8:13, which plots vertical slices from Figure 8:12 to show the diminishing benefit of reconfiguration flexibility. In this plot the reconfiguration flexibility scale is presented as a fraction. For example, flexibility of +/-32 in a product range of 128 is translated into a flexibility of +/-0.25.

Figure 8:13 Benefit of reconfiguration flexibility at different pipeline lengths (Two-way, Variety 1024. Note flexibility on the horizontal axis is quantified as flex/variety)

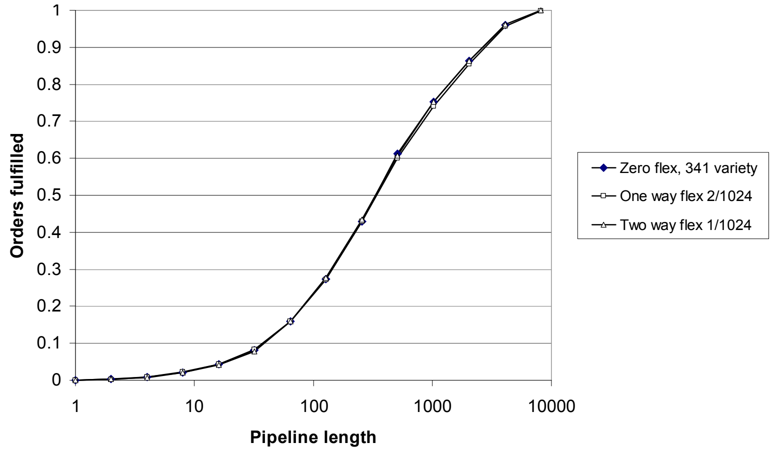


When the search policy is to search for the closest specification, it is found that increasing reconfiguration flexibility is equivalent to reducing the produced variety.Two-way reconfiguration flexibility of +/-1 is equivalent to reducing the produced variety by $^1/_3$ since a product in the pipeline can fulfil a customer seeking one of three variants (except for the highest and lowest product as indicated in Table 8:2, which creates an equivalence error that tends to zero as variety tends to infinity). Hence, flexibility of +/-1 in a product range of 1024 is (nearly) equivalent to zero flexibility in a product range of 1024/3 (~341). It is also (nearly) equivalent to one-way flex of +2. This is shown in a comparison of results from two-way and one-way flexibility with the results of a system without flexibility in Figure 8:14, where the differences between the three are difficult to discern visually at this scale of plot.

Table 8:2 Products that can be used to fulfil a customer at three levels of reconfiguration flexibility when the product range is 5

Customer requested specification	Reconfiguration flexibility level		
	0	+/- 1	+ 2
5	5	4, 5	3, 4, 5
4	4	3, 4, 5	2, 3, 4
3	3	2, 3, 4	1, 2, 3
2	2	1, 2, 3	1, 2
1	1	1, 2	1

Figure 8:14 **Comparison of Two-way and One-way reconfiguration flexibility and reduced variety (Zero flex, variety 341; One-way flex +2, variety 1024; Two-way flex+/-1, variety 1024)**

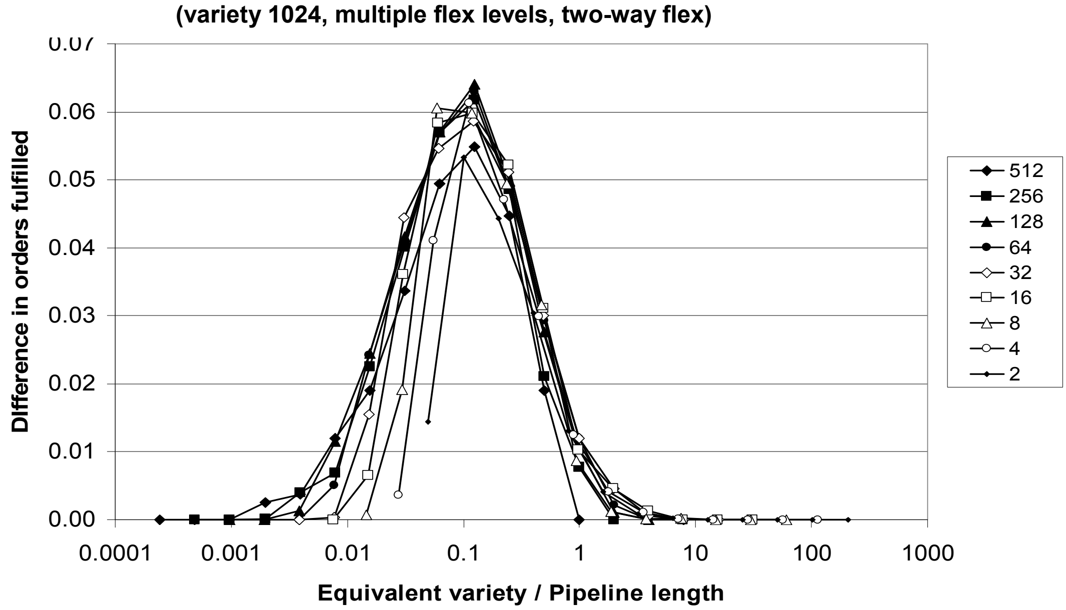


8.3.3.2 *Searching for the first available product*

Using the policy of searching for the first available product increases the proportion of customers fulfilled at all levels of reconfiguration flexibility compared to using the policy of searching for the closest specification. Figure 8:15 shows that when the ratio of equivalent variety/pipeline is ~0.1 there is a ~6% greater likelihood of matching a customer with a product in the pipeline if a first available search policy is used as opposed to a closest specification policy. The difference between the policies lessens as the ratio becomes large or small.

These results are consistent with the insight from Figure 8:3 (on page 69) that fulfilment is affected by how long the allocated products reside in the pipeline. By searching for the first available product, products are found that are further downstream the pipeline than when using the 'closest specification' search method.

Figure 8:15 **Difference in fulfilment between 'First available' and 'Closest specification' (variety 1024, multiple flex levels, two-way flex)**



8.4 Phase 2: Full VBTO system

Here the full VBTO system with the three fulfilment mechanisms is studied. Now a customer can be fulfilled by a product from stock, by a BTO product or from the pipeline.

From the earlier investigation above it is known that the likelihood of finding a match in the pipeline alone is predictable and is governed by the ratio of product variety and pipeline length. A question to be investigated here is whether there are equally consistent and predictable relationships for all three fulfilment mechanisms when operating together.

In the simulation experimentation conducted here, stock is allowed to form and no restriction is placed on the number of products in stock. However, because customer arrival rate and production rate are equal and constant, there are a constant number of unallocated products available in the system (if a matching product is not found in stock or in the pipeline a BTO order is placed). To be clear, on each occasion a customer is fulfilled from stock or from the pipeline (and thereby deplete the available products by one) an unallocated product is fed into the pipe. When a customer is fulfilled by a BTO product, the entry of the BTO product blocks entry of an unallocated product and hence the total number of available products in the system is unchanged.

As earlier, the system is studied with feed into the pipeline and customer demand modelled as uniform random distributions. Later the impact of skew is studied. Reconfiguration flexibility is also introduced as is the additional factor of customer compromise and their effects are compared.

8.4.1 Contribution of the Pipeline

The first study compares the full VBTO system with the 'Conventional' two mechanism system, i.e. one that lacks pipeline fulfilment. In a Conventional system a customer can be fulfilled only by a product from stock or by requesting a BTO product. The unallocated products in the pipeline are hidden from the customer.

The points of interest are how the addition of pipeline fulfilment alters the fulfilment patterns, stock holding and customer waiting times.

8.4.1.1 Observations on fulfilment mechanisms

Figure 8:16, Figure 8:17 and Figure 8:18 clearly show that for both the VBTO and the Conventional systems the relationship between fulfilment mechanism and the ratio of product variety to pipeline length is fundamental. In each graph the results from systems of several pipeline lengths are plotted and in all cases they show consistency against the variety/pipeline ratio with minor deviations due to numerical issues in deriving simulation estimates at very low levels of variety / pipeline ratio.

These are cumulative plots, e.g. in Figure 8:16, the area below the line is stock fulfilment, and above the line it is BTO fulfilment. At a variety/pipeline ratio of 1, just under 40% of customers are fulfilled from stock and 60% by BTO, approximately. In Figure 8:17, the bottom area is stock fulfilment, the middle zone is fulfilment from the pipeline (pipe) and the upper area is BTO fulfilment. In this graph, at a variety/pipeline ratio of 1 the fulfilment is 30% from stock, 20% from pipeline and 50% by BTO, approximately.

In all three graphs, but more obviously in Figure 8:17 and Figure 8:18 there is numerical error from simulation experimentation in the plots toward the left of the graphs. By averaging across all pipeline lengths, clean plots for the forward and backward searched VBTO systems are created (Figure 8:19 and Figure 8:20 which are enlarged in landscape format).

Comparing the forwards and backwards searches finds the BTO proportions to be the same across all variety/pipeline ratios. However, the role of stock is different, with more customers fulfilled from stock using a forwards search than a backwards search (also see Figure 8:21 and section 8.4.1.2 for analysis of stock).

Compared to the Conventional system, in the VBTO system the switchover to BTO fulfilment is delayed to higher variety/pipeline ratios. In Figure 8:21 the mechanism boundaries from the VBTO and Conventional systems are plotted to highlight this difference. When the variety/pipeline ratio is in the region of 0.01 to 0.1, the BTO proportion in a VBTO system is at the level it would be in a Conventional system which had an order of magnitude less variety.

At very low variety/pipeline ratio a VBTO system using the forwards search is almost equivalent to a Conventional system, with approaching 100% fulfilled from stock. The backwards search is distinct, with far fewer customers fulfilled from stock (between 50% & 60% at variety/pipeline ratio of 0.01).

At a variety/pipeline ratio of ~10, the VBTO and Conventional systems are equivalent.

Figure 8:16 **Fulfilment by mechanism for the Conventional system, *backwards* search. (Cumulative plot showing stock at bottom and BTO at the top)**

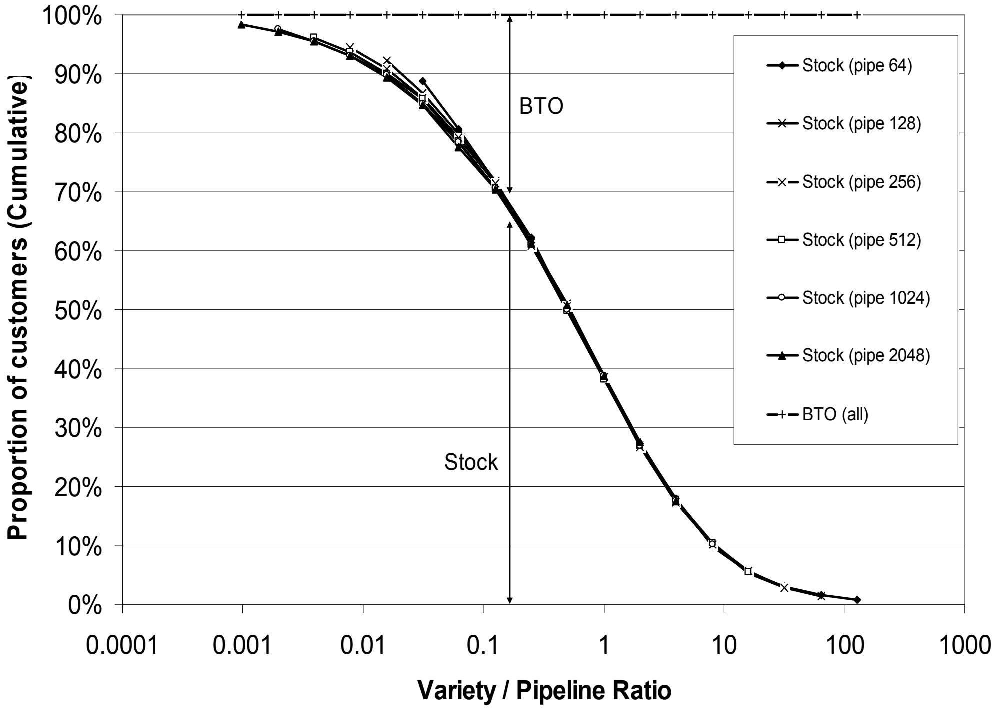


Figure 8:17 **Fulfilment by mechanism for the VBTO system, *backwards* search. (Cumulative plot showing stock at bottom, pipeline in the middle, and BTO at the top)**

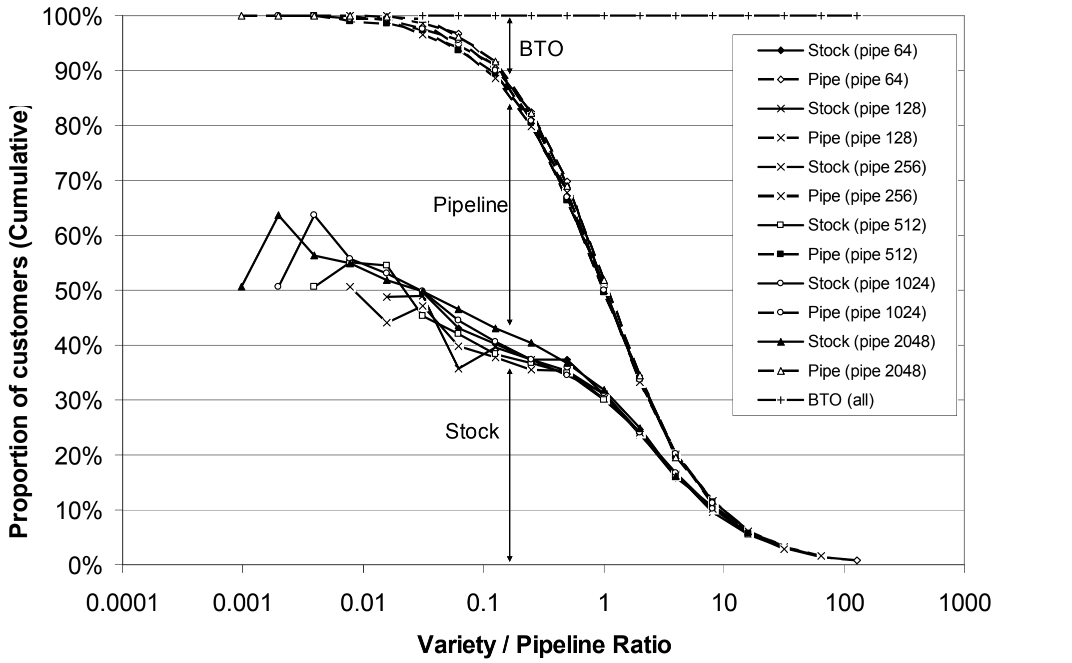


Figure 8:18 **Fulfilment by mechanism for the VBTO system, *forwards* search. (Cumulative plot showing stock at bottom, pipeline in the middle, and BTO at the top)**

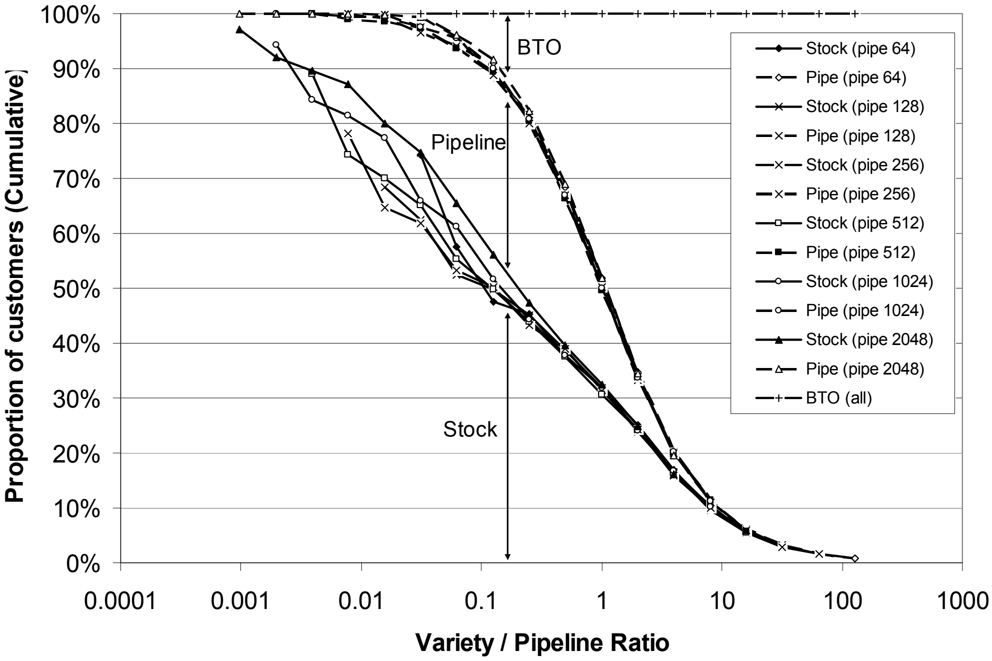


Figure 8:19 Fulfilment by mechanism for the VBTO system, *backwards* search. (Cumulative plot showing stock at bottom, pipeline in the middle, and BTO at the top)

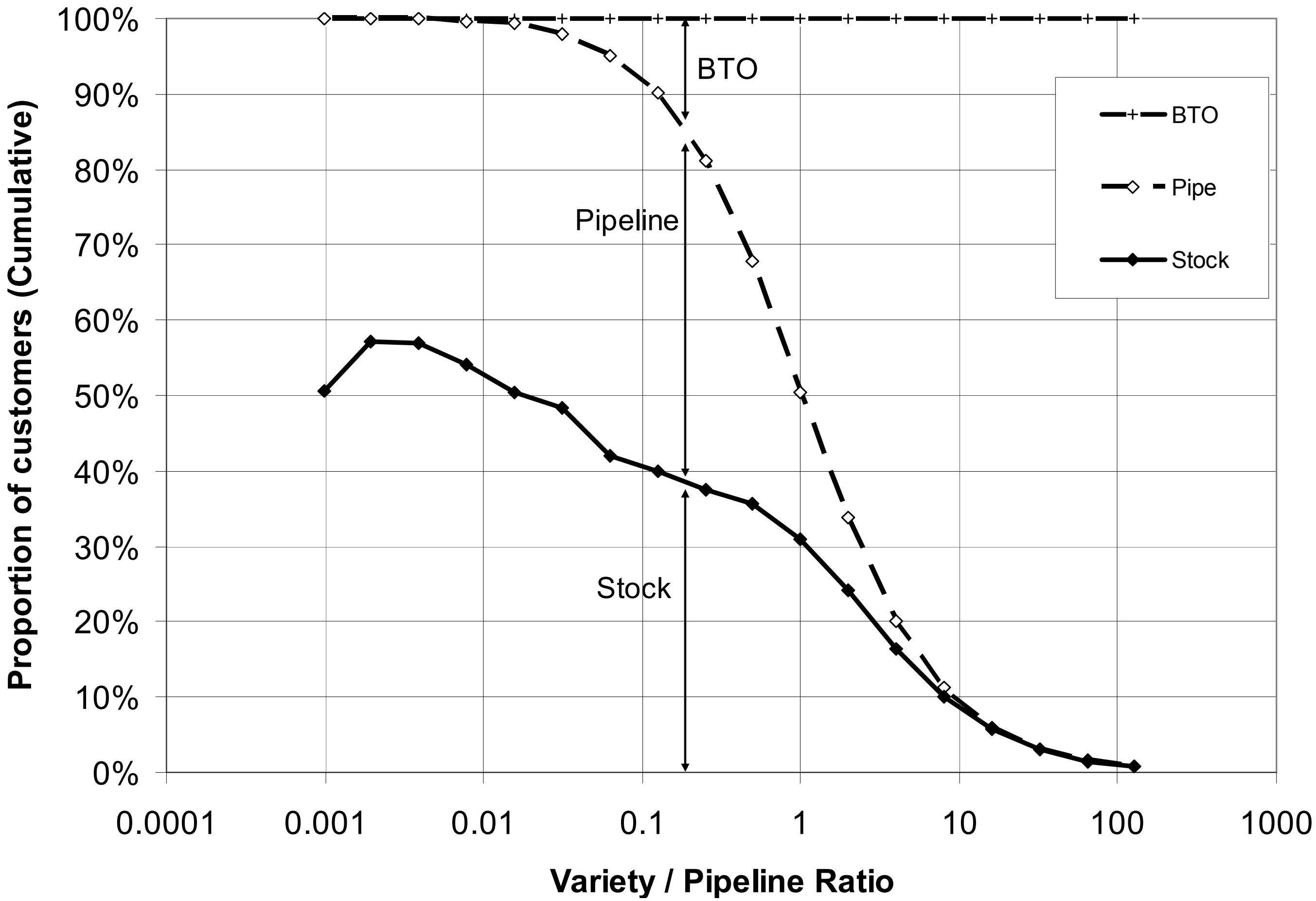


Figure 8:20 Fulfilment by mechanism for the VBTO system, *forwards* search. (Cumulative plot showing stock at bottom, pipeline in the middle, and BTO at the top)

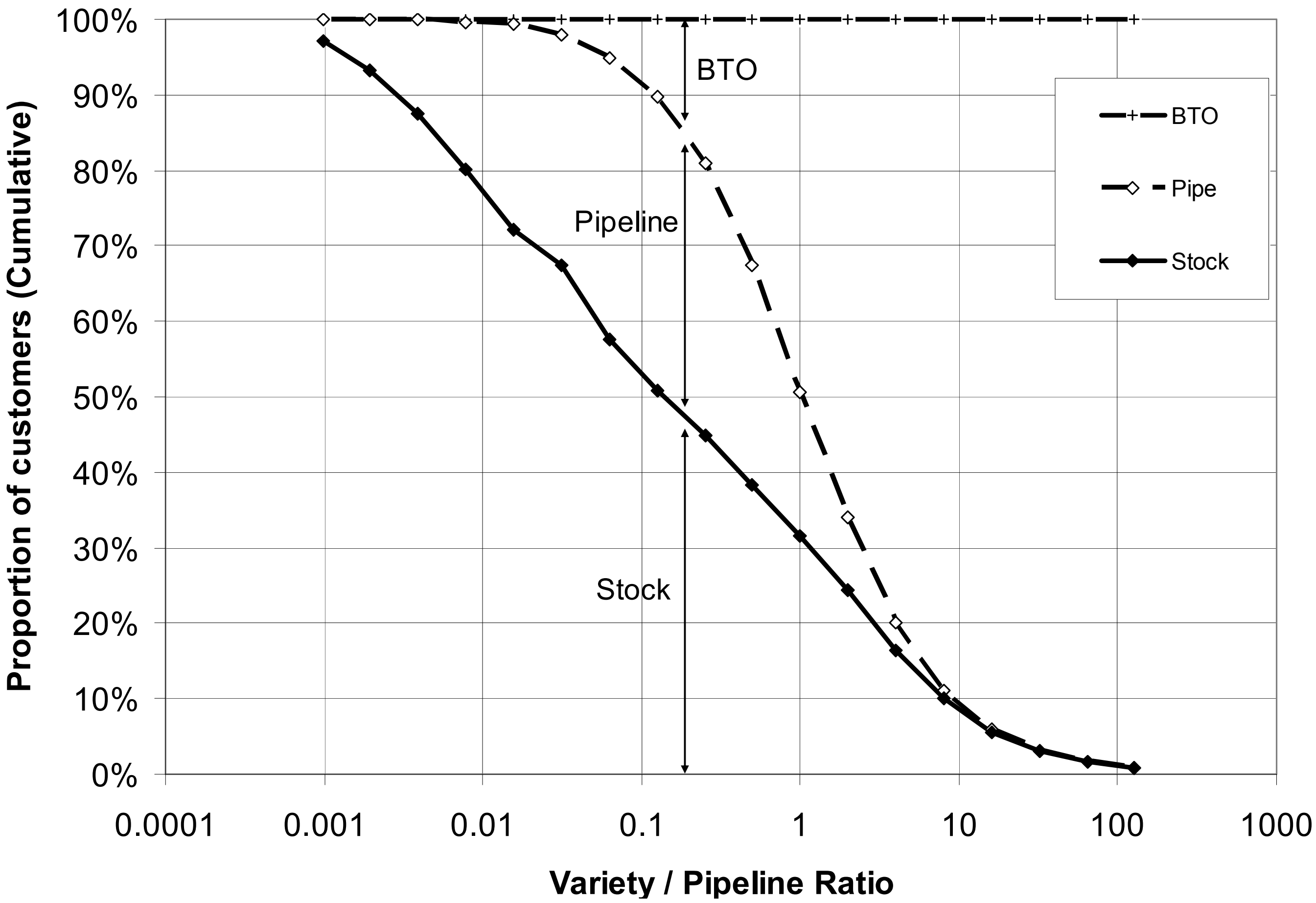
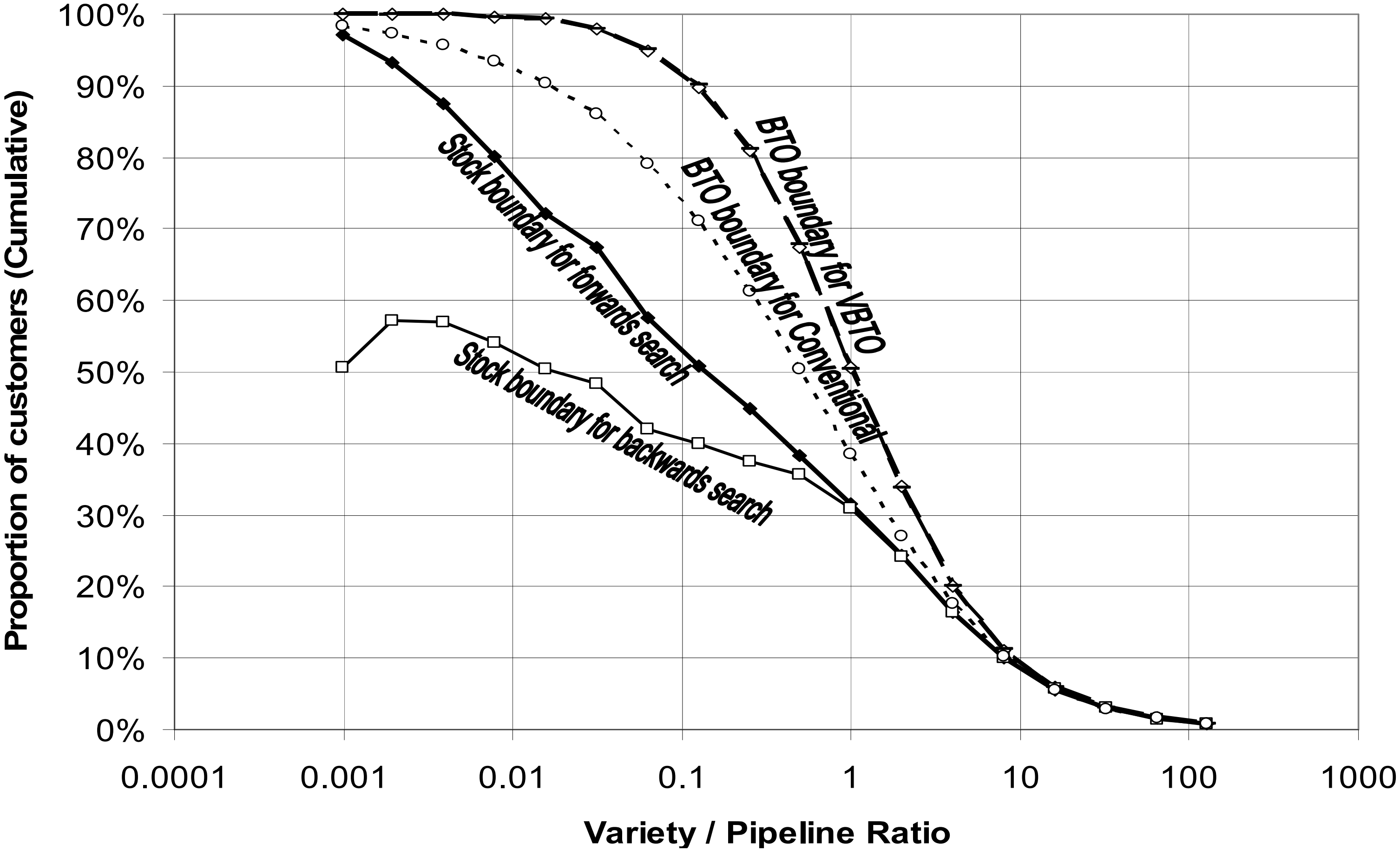


Figure 8:21 Comparison of stock and BTO boundaries for the VBTO system (*forwards* and backwards searches) and Conventional system (Cumulative plot)



Comparing the VBTO and Conventional systems in further detail reveals unexpected differences in respect to stock levels and customer waiting time.

8.4.1.2 *Observations on stock levels*

Comparison of Figure 8:16 and Figure 8:17 shows that at low variety/pipeline ratios the dominant fulfilment mechanism is stock in the Conventional system and approximately double the proportion of customers are fulfilled from stock in this system than in the VBTO system using a backward search. From this observation it might be expected that there is double the amount of stock in the Conventional system than in the VBTO system. However, the reverse is the case as shown in Figure 8:22 and Figure 8:23. At variety/pipeline ratios below 1 the VBTO system carries more stock than the Conventional system, approaching twice as much at a ratio of 0.01 (Figure 8:23).

Figure 8:22 Comparison of average stock levels in the VBTO and Conventional systems

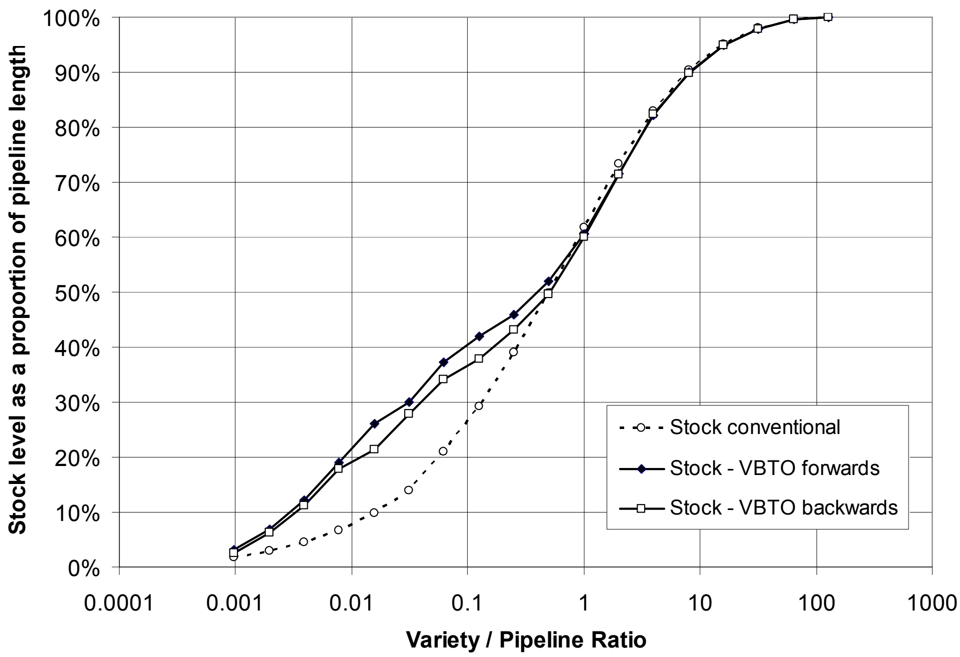
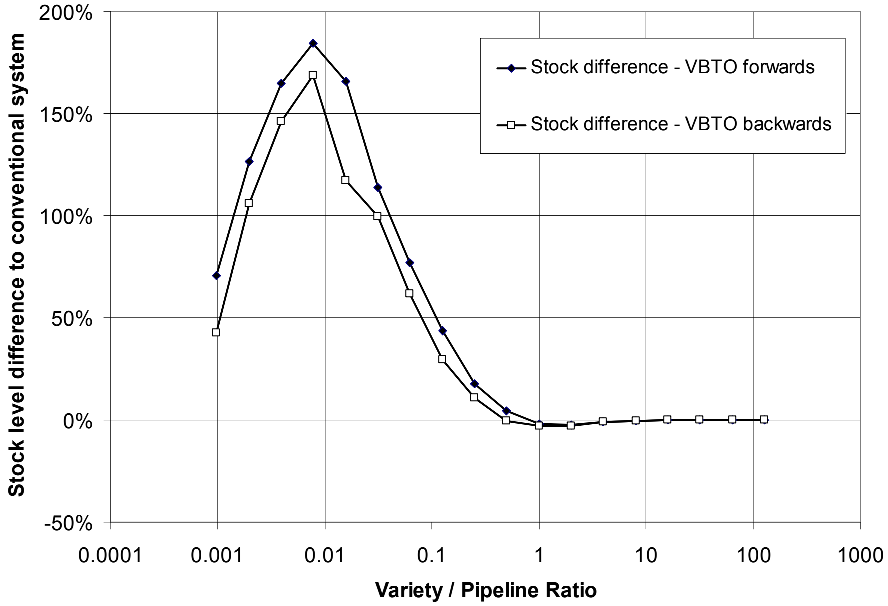


Figure 8:23 Percentage difference in average stock levels from the Conventional system



Analysis of stock

Examination of stock in the VBTO system reveals the mix of products in stock to be highly skewed compared to the Conventional system. A random snapshot of the stock in a VBTO system (using a backward search, pipeline length of 512) with variety of 4 illustrates the condition: of the 57 products in stock there were none of type '1', 8 of type '2', 5 of type '3' and 44 of type '4'. The oldest 33 products in stock were all type '4'.

The effect of this is that the stock in the VBTO system has less coverage than the stock in the Conventional system, where coverage is the proportion of product variants for which there is at least one available. Coverage for the two systems is presented in Figure 8:24 and Figure 8:25 and comparison of these plots with Figure 8:16 and Figure 8:17 reveals that coverage is closely linked to fulfilment. Note, in the coverage plots, the coverage of stock is plotted and the coverage of the combined stock and pipe is also plotted (as dashed line). The pipe is invisible in the conventional system, therefore the dashed line in Figure 8:24 is the maximum coverage achievable.

Figure 8:24 Coverage in the Conventional system

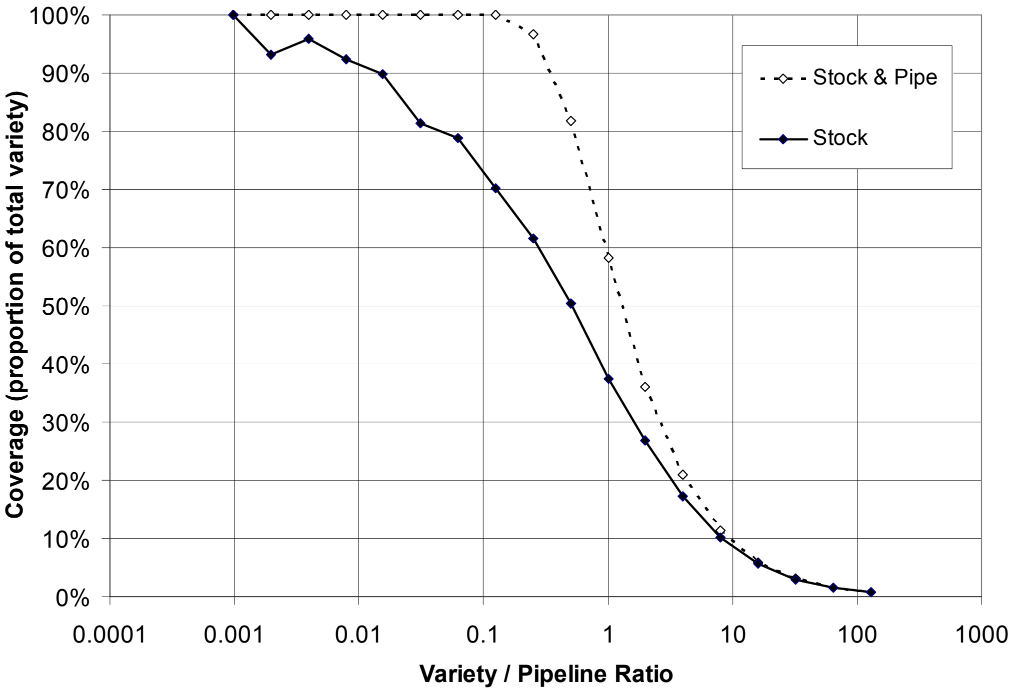
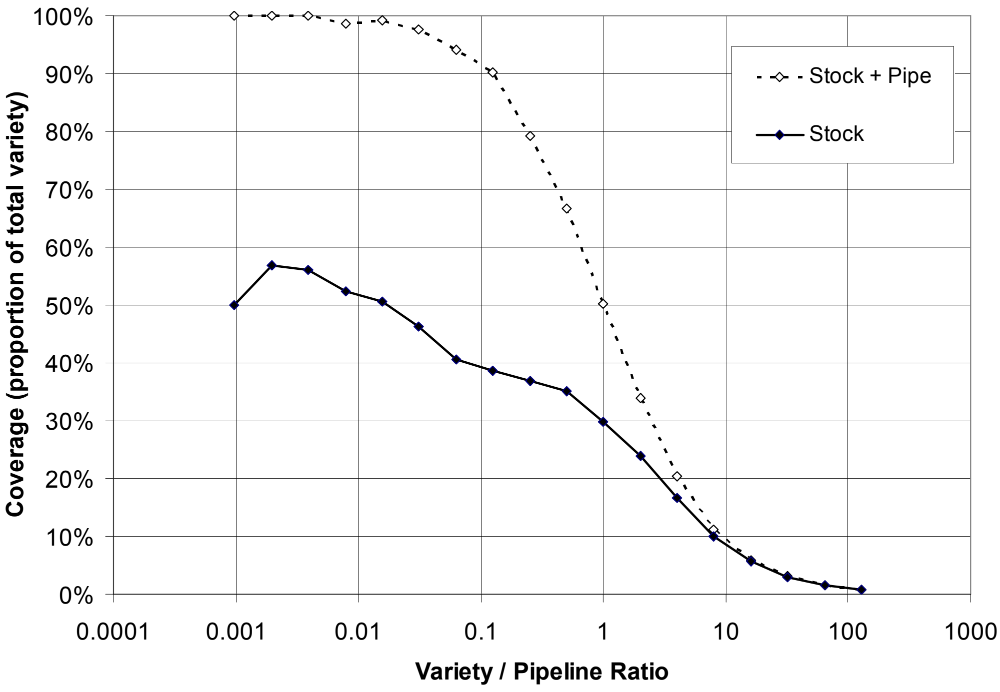


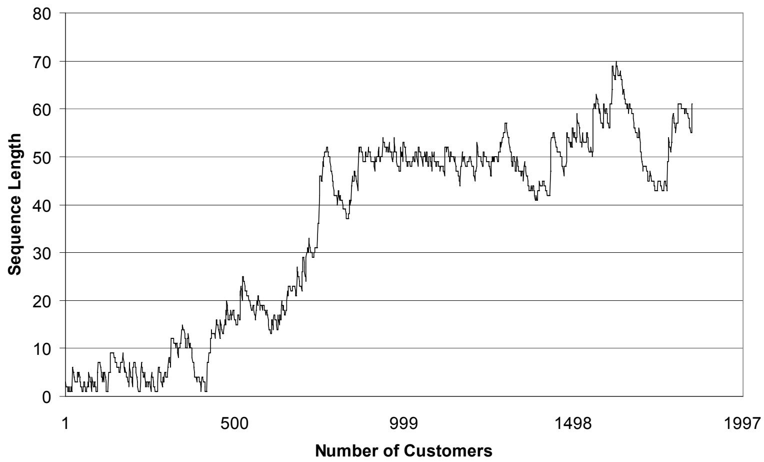
Figure 8:25 Coverage in the VBTO system (*backwards* search)



The cause for this has been found to lie in the interaction between the sequence of products in the pipeline and the sequence of customers. The feed of products into the pipeline is a random sequence, and the customers also arrive in a random sequence, but the interaction between the two sequences leads to the pipeline being stripped of its randomness, resulting in an unrepresentative distribution of variants replenishing stock.

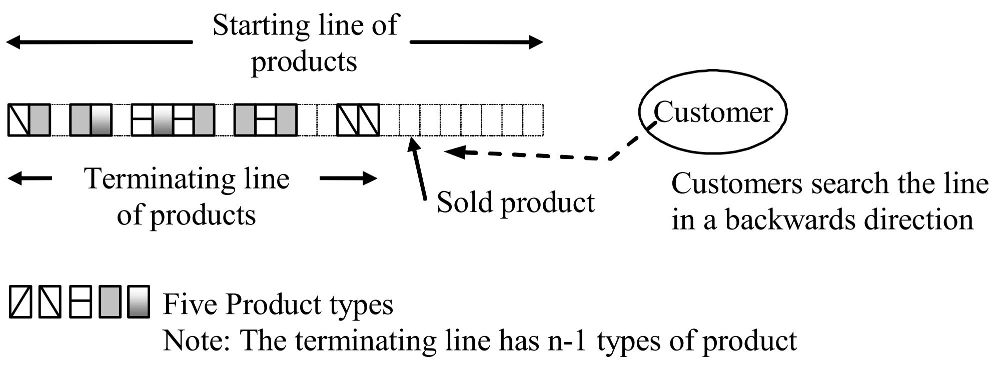
To illustrate the stripping phenomenon, a long pipeline has been generated of a random sequence of 4 products, which has then been searched (using a backward search) by a random sequence of customers. Figure 8:26 shows that after approximately 500 or so customers, almost the first 20 available products at the front of the pipeline are of the same type. After 1000 customers, the first 50 or so available products are identical, and at one point the first 70 products are identical. This outcome illustrates the stripping behaviour and suggests strongly that the sequence of available products in the pipeline is no longer random.

Figure 8:26 Length of sequence of identical products at the front of the pipeline



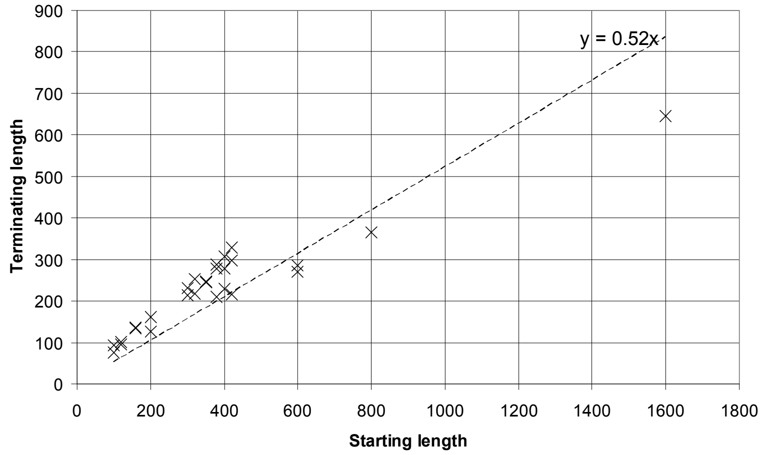
The Chi-square goodness-of-fit test is appropriate for testing the randomness of a pipeline and has been used to assess how quickly the pipeline loses its randomness. A simulation has been created in which a static line of products is generated and then searched by a sequence of customers. Different lengths of static lines have been simulated. Each simulation terminates on the first occasion that a customer cannot find an exact match in the line. For example, if the line started with a mix of 16 products, the line at the moment of termination will have 15 products only. The randomness of the line is then assessed using the Chi-square test and a value of less than 1% suggests strongly it is unlikely to be random. The mechanics of the simulation are summarised in Figure 8:27.

Figure 8:27 Schematic of the Terminating simulation



The system has been studied at two variety levels – 32 and 256 products. Figure 8:28 plots the starting pipeline length against the termination length (i.e. the length the pipeline has been reduced to by the time a customer cannot find a match in the pipeline). In neither case does it take long for the terminating condition to be reached. In Figure 8:29 the chi-square value is plotted against the number of customers fulfilled by the time the terminating condition is reached and these plots indicate that for variety of 32 the pipeline is no longer random after approximately 100 customers, and for variety 256 randomness is lost after approximately 150 customers.

Figure 8:28 Graphs of Terminating length against Starting length for variety 32 and 256



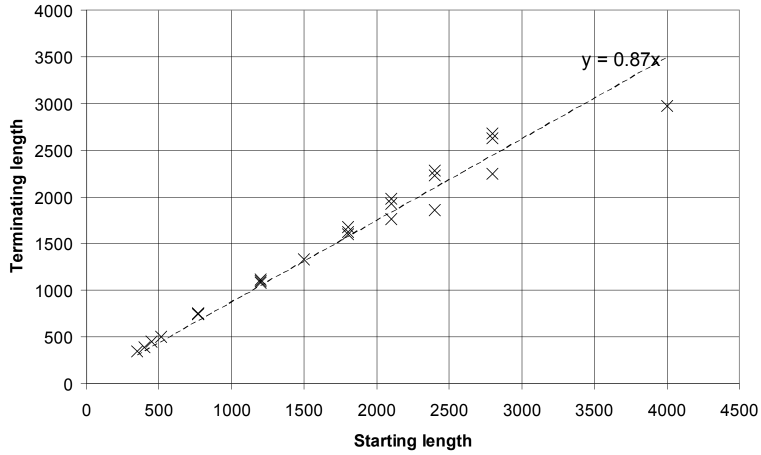
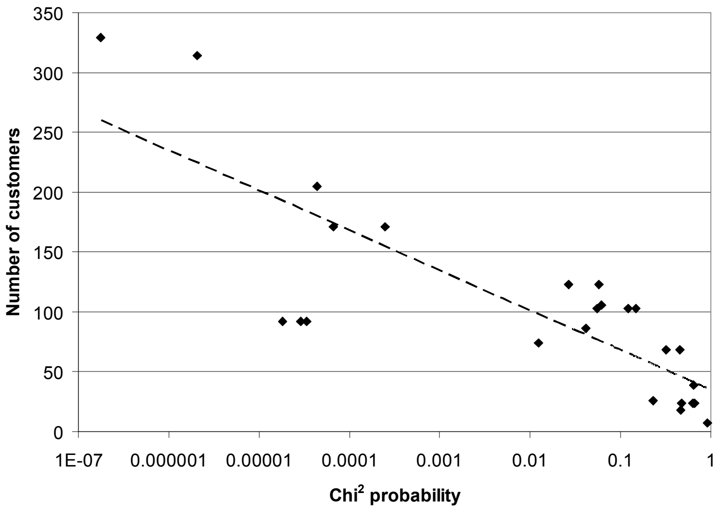
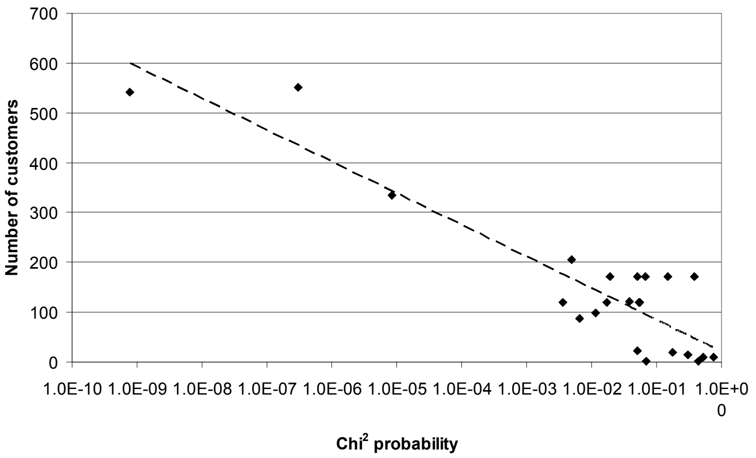


Figure 8:29 Plots of Chi-square probability against number of customers fulfilled when the Terminating condition is reached for variety 32 and 256





8.4.1.3 *Observations on customer waiting times*

Although the VBTO system has a lower proportion of customers being fulfilled by BTO the average customer waiting time is greater than in the Conventional system, as shown in Figure 8:30 and Figure 8:31.

This comparison of average waiting time does not reflect that in the Conventional system customers either are serviced immediately from stock or wait for a BTO product to come through the entire pipeline so that the average waiting time can be misleading, whereas in the VBTO system there is a spread of fulfilment times. This is illustrated in Figure 8:32, which presents the cumulative distribution of waiting times in a VBTO system when product variety is 32 and the pipeline length is 512. Although the average customer waiting time in the VBTO system is 189 time periods compared to 114 in the Conventional system, half of all VBTO customers are fulfilled in 117 time periods or less. In the Conventional system 22% of customers wait the length of the pipeline (which is 512 time periods) whereas only 7% of customers wait for longer than 500 time periods in the VBTO system.

Figure 8:30 Comparison of average waiting times in the VBTO and Conventional systems

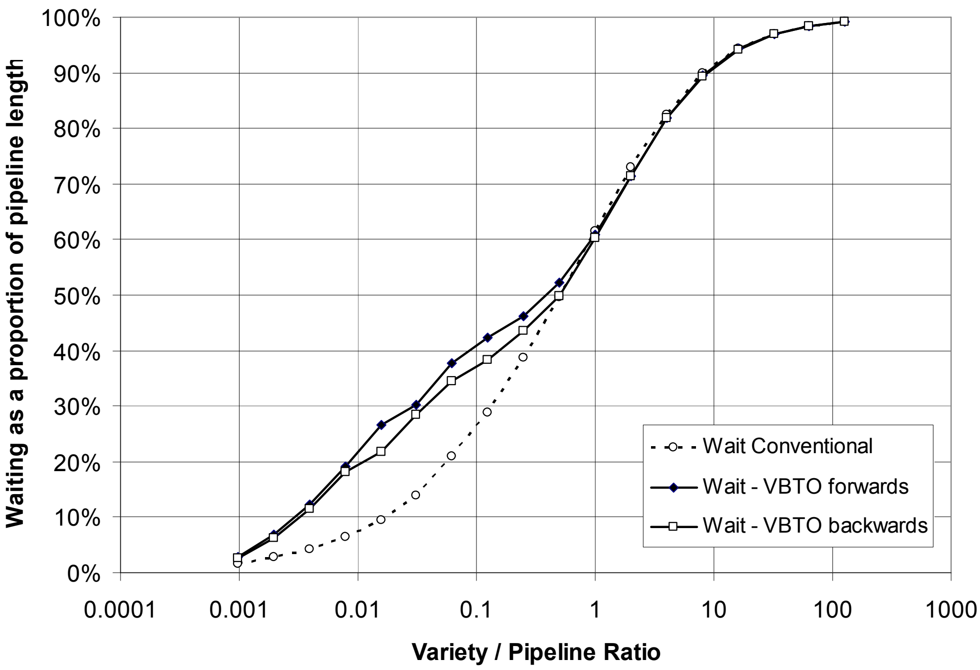


Figure 8:31 Percentage difference in average waiting time from the Conventional system

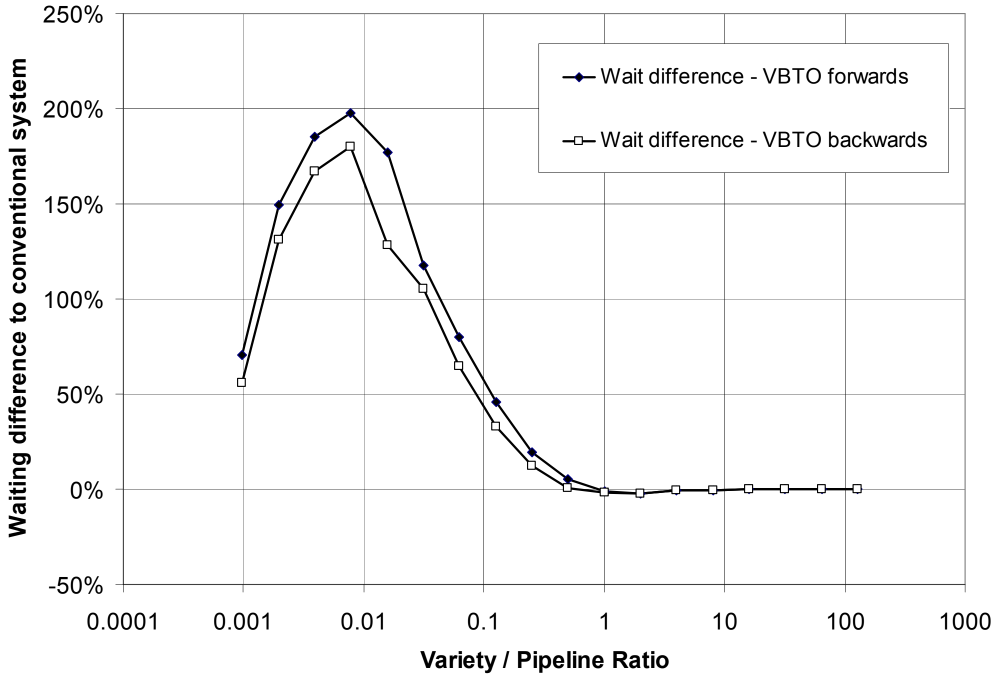
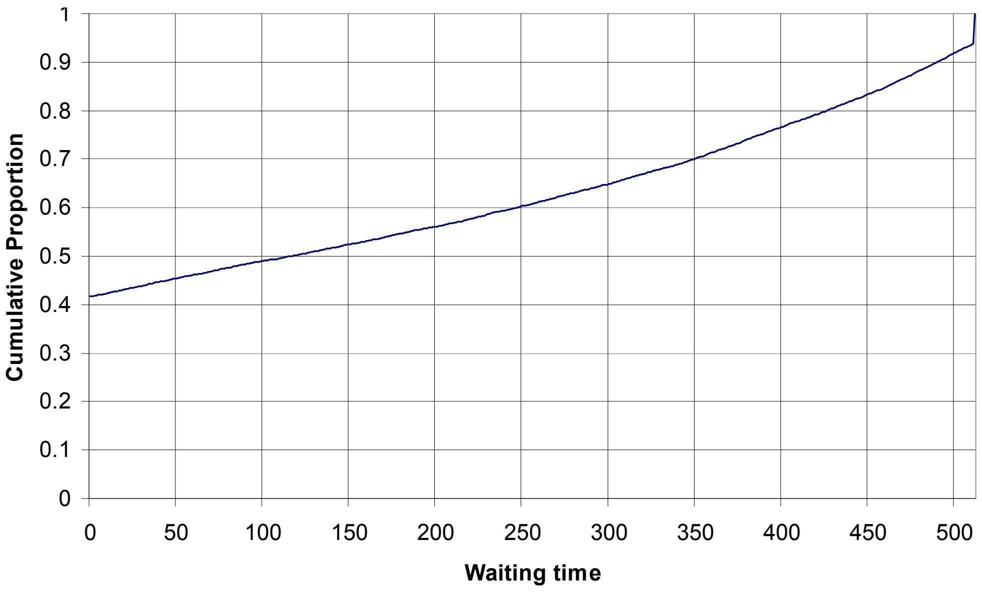


Figure 8:32 Cumulative distribution of customer waiting times for the VBTO system (pipeline 512, backwards search, variety 32, compiled from 16000 customers)



8.4.2 Impact of the number of products available in the system

In the experiments presented up to this point, the system has been primed by filling the pipeline. As has been explained earlier, because the customer arrival rate is fixed and equal to the production rate, the number of available products in the system remains constant throughout an experimental run. In this section the priming conditions are varied, which means the VBTO system is being studies with different amounts of available products. Five conditions are examined;

- the pipeline is half primed (identified as the '-½' condition);
- the pipeline is fully primed ('0' condition);
- the system is primed with a full pipeline and stock holds the equivalent of half a pipeline ('+½' condition);

- the system is primed with a full pipeline and stock holds the equivalent of a whole pipeline ('+1' condition);
- the system is primed with a full pipeline and stock holds the equivalent of two pipeline lengths ('+2' condition).

Across the variety / pipeline ratios analysed all three fulfilment mechanisms are altered by the number of available products (Figure 8:33). As would be expected, stock fulfilment is greater after the system has been primed with more products Average waiting time is reduced (Figure 8:34) and stock holding increases (Figure 8:35). The results of this section are relevant to a producer who is launching a product.

Figure 8:33 Fulfilment by mechanism at different priming conditions, *backwards* search. (Cumulative plot: stock at bottom, pipeline in the middle, and BTO at the top, pipeline 512)

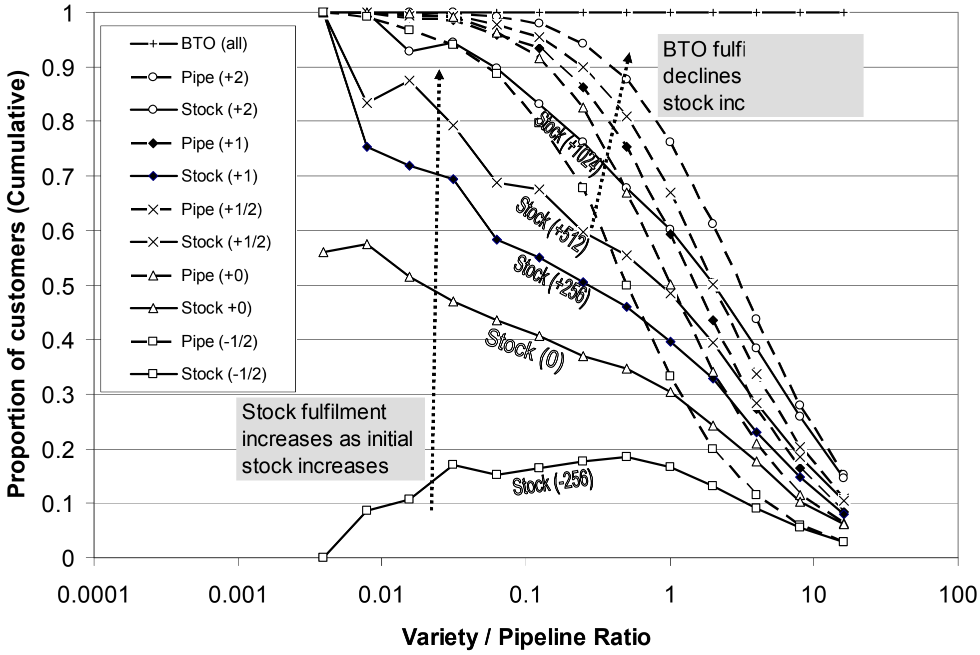


Figure 8:34 Average Waiting time at different priming conditions, *backwards* search (pipeline 512)

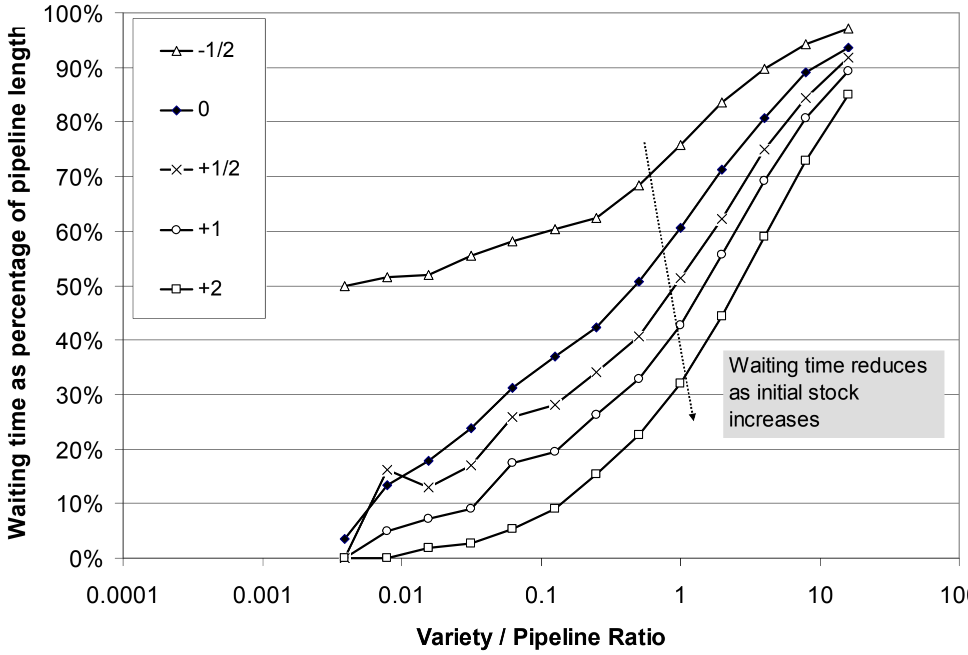
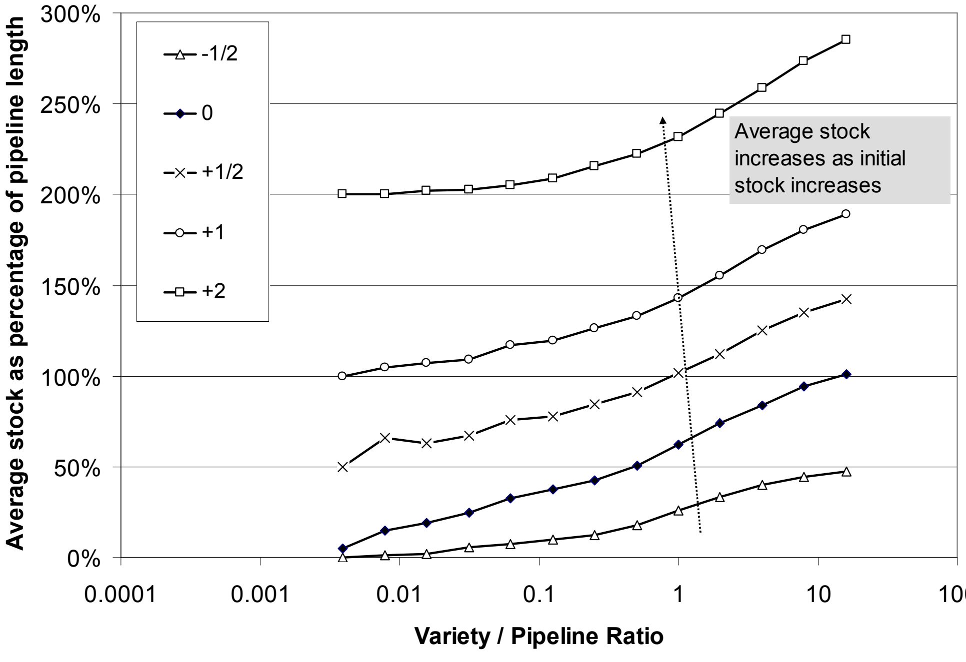


Figure 8:35 Average stock holding at different priming conditions, *backwards* search (pipeline 512)



8.4.3 Impact of skew

It was observed that introducing skew into the demand distribution altered the fulfilment likelihood in the pipeline only system (section 8.3.2 above). In the full VBTO system the pattern of fulfilment is altered also. Figure 8:36 shows how the roles of stock, pipeline and BTO fulfilment change as skew is introduced into a VBTO system using the backward search. Stock fulfilment increases and BTO fulfilment declines as skew increases, across all variety/pipeline ratios. Note, at the lowest levels of variety for the highest skew levels the role of the pipeline increases, and this is verified at a second pipeline length in Figure 8:37. This is not surprising as the lowest levels of variety studied are 2, and 4, and when the skew is 90/10, virtually all products in the system are of one type.

Average waiting time and stock holding are impacted also as shown in Figure 8:38 and Figure 8:39. Both are reduced, and the magnitude of the reduction appears to be constant across the range of variety/pipeline ratios simulated.

Skew has a similar impact in a Conventional system, with fulfilment shifting from BTO to the stock mechanism (Figure 8:40), waiting time (Figure 8:41) and stock holding (Figure 8:42) declining.

Figure 8:36 Fulfilment by mechanism at different skew levels, *backwards* search. (Cumulative plot: stock at bottom, pipeline in the middle, and BTO at the top, pipeline 512)

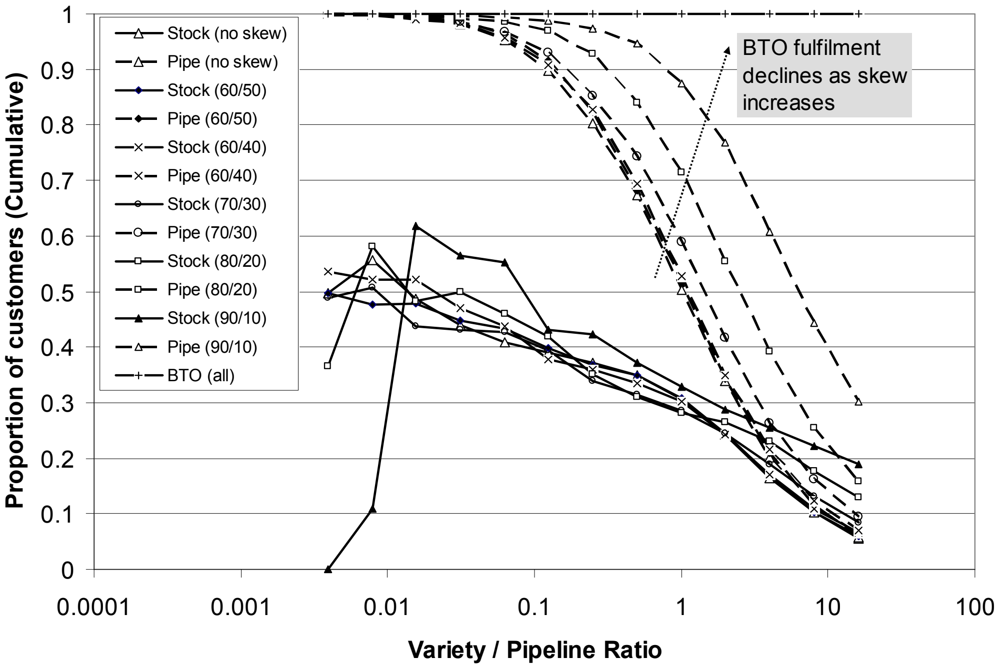


Figure 8:37 Fulfilment by mechanism at 90/10 skew levels, two pipeline lengths (128 and 512), *backwards* search. (Cumulative plot: stock at bottom, pipeline in the middle, and BTO at the top)

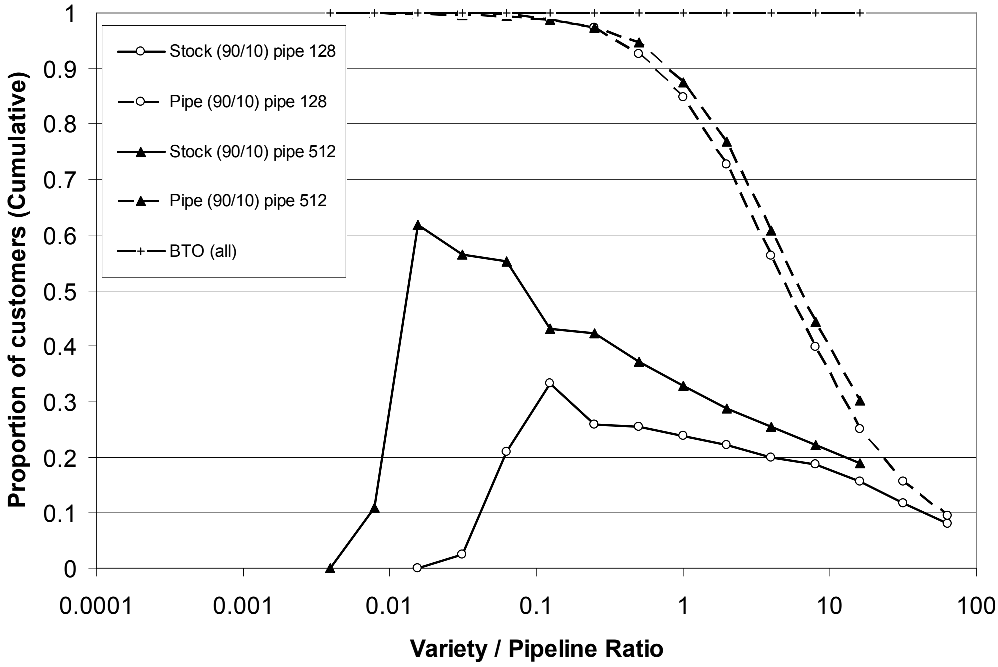


Figure 8:38 Average Waiting time at different skew levels, *backwards* search (pipeline 512)

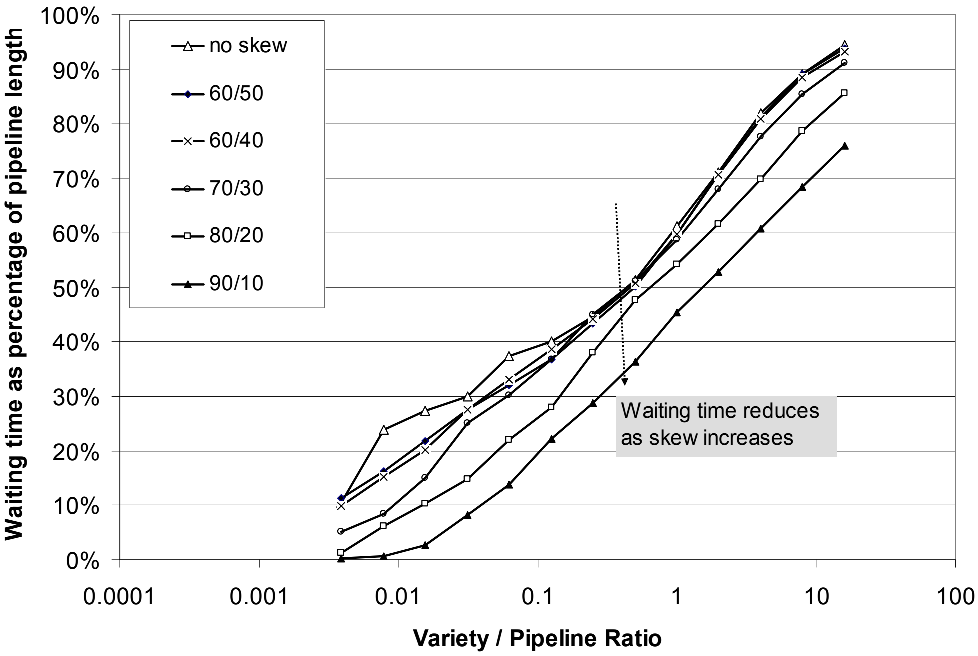


Figure 8:39 Average stock holding at different skew levels, *backwards* search (pipeline 512)

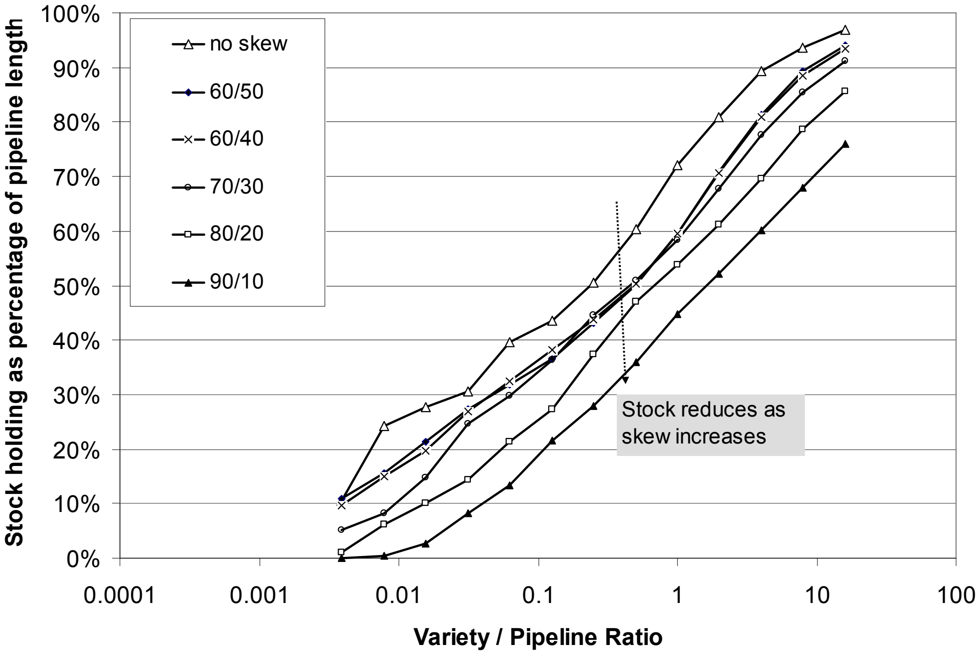


Figure 8:40 Fulfilment by mechanism in a Conventional system, with no skew and 90/10 skew, *backwards* search. (Cumulative plot showing stock at bottom, BTO at the top, pipeline 512)

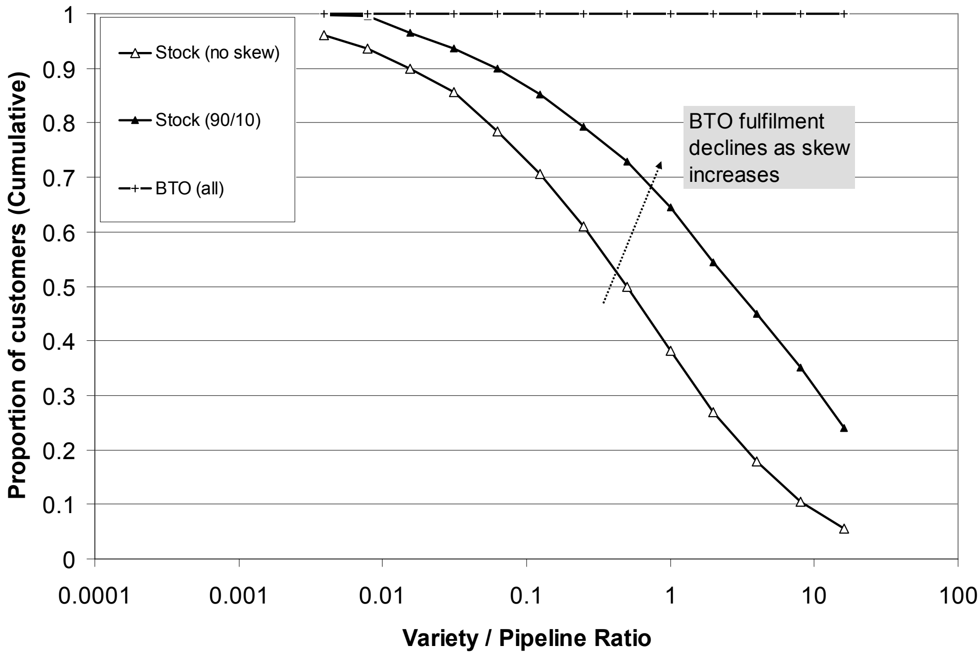


Figure 8:41 Average waiting time in a Conventional system, with no skew and 90/10 skew, *backwards* search (pipeline 512)

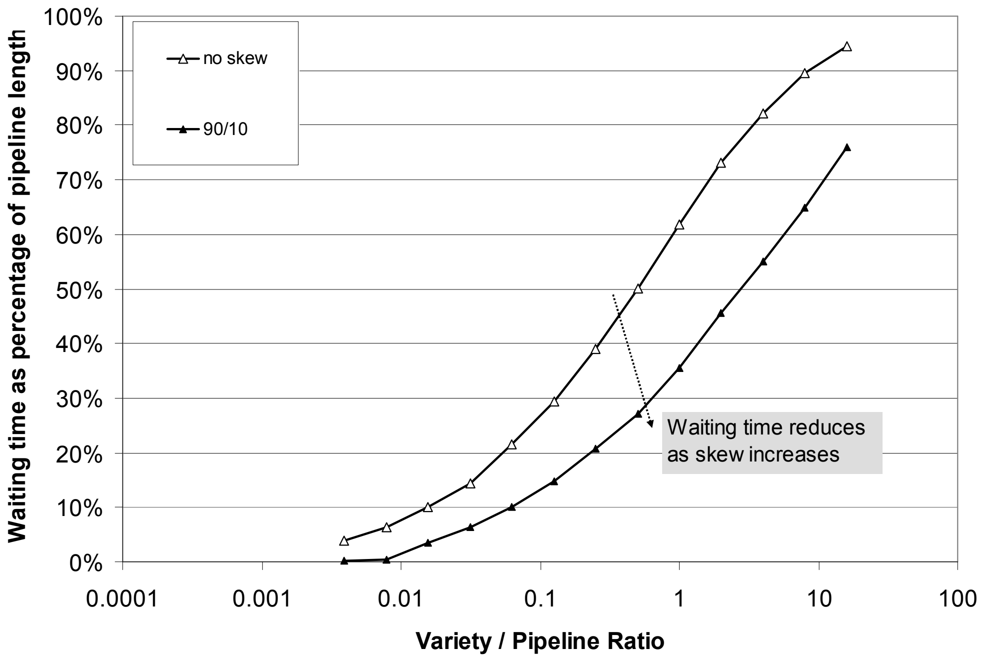
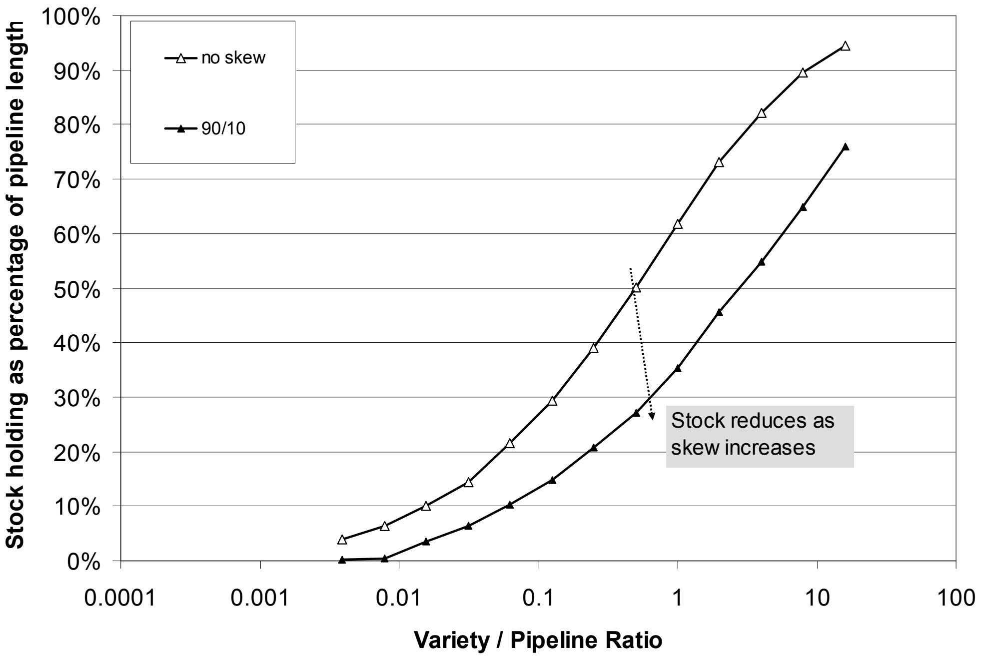


Figure 8:42 Average stock holding in a Conventional system, with no skew and 90/10 skew, *backwards* search (pipeline 512)



8.4.3.1 *Skew and waiting time*

In a VBTO system, introducing skew leads to significant differences in the fulfilment patterns across the product range. In a system with 32 variants and a skew of 70/30, the relative frequency of each variant is shown in Figure 8:43. For each variant the proportions of customers fulfilled by each mechanism are shown in Figure 8:44, which shows pipeline fulfilment to be dominant for the most frequent variants, but this mechanism declines and stock fulfilment becomes dominant until the extreme variants which are fulfilled via the stock and BTO mechanisms only.

Average waiting time (Figure 8:45) is not constant across the range. For the most frequent variant the average waiting time is about 60% of the pipeline, and this gradually drops to below 10%, before rising sharply at the right tail.

In the Conventional system the pattern of fulfilment and waiting time is almost uniform, with only the rare variants having a different split between the mechanisms (Figure 8:46) and different waiting time (Figure 8:47).

The different patterns between the VBTO and Conventional systems can be linked to the behaviour underlying the difference in stock levels investigated in section 8.4.1.2 (page 84). The near uniform behaviour in the conventional system is expected to be due to the stock mix being in closer harmony with the demand mix, whereas the stock mix of the conventional system will be altered by the 'stripping' phenomenon.

Figure 8:43 Distribution for 70/30 skew

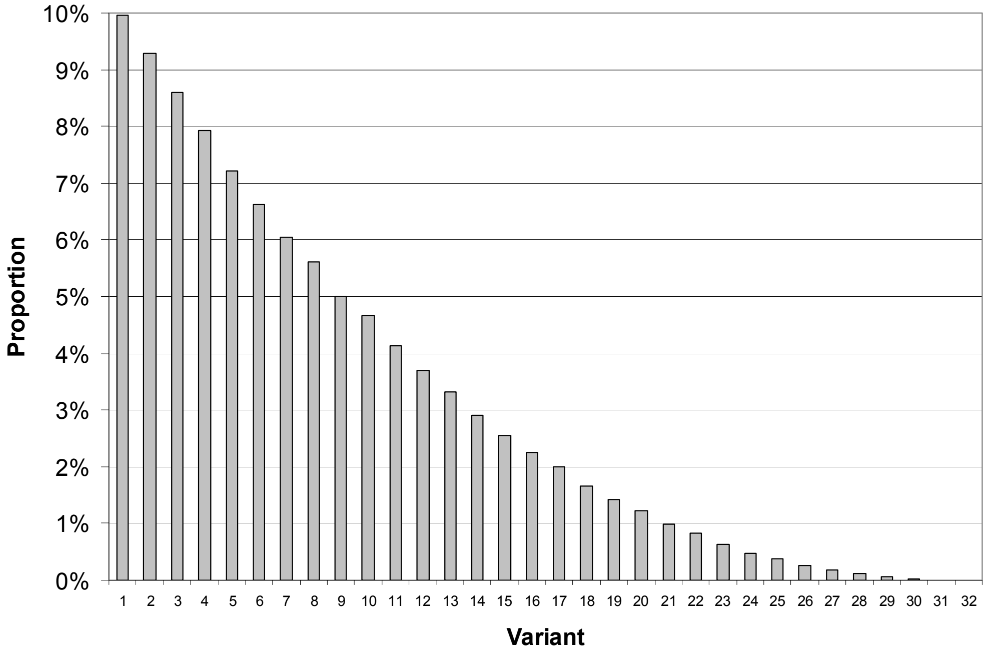


Figure 8:44 Fulfilment mechanism for each variant (skew 70/30, variety 32)

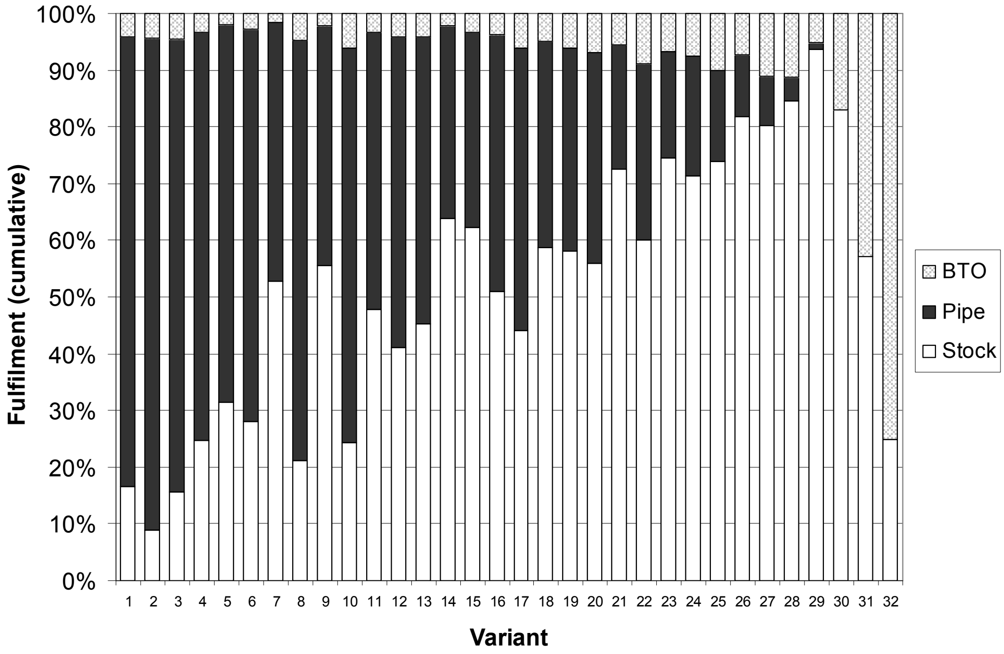


Figure 8:45 Average customer waiting time for each variant in a VBTO system (skew 70/30, variety 32)

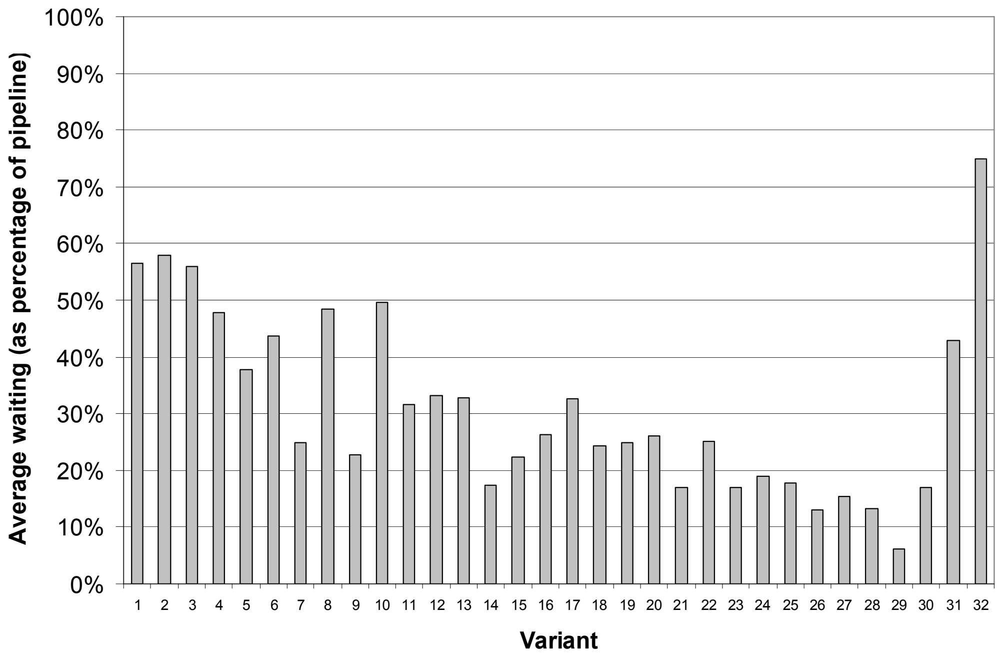


Figure 8:46 Fulfilment mechanism for each variant in a Conventional system (skew 70/30, variety 32)

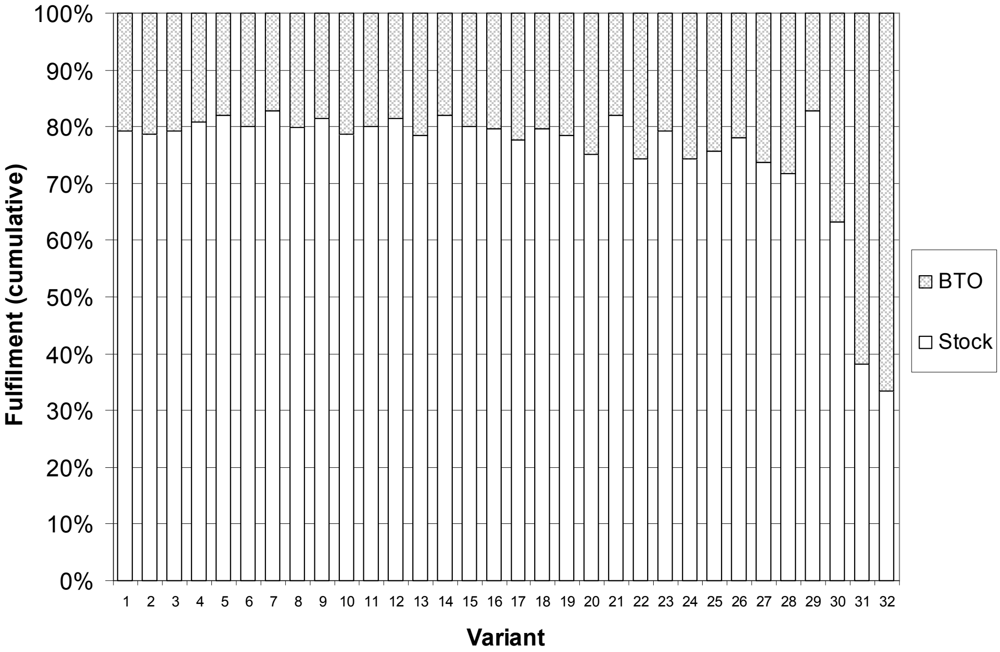
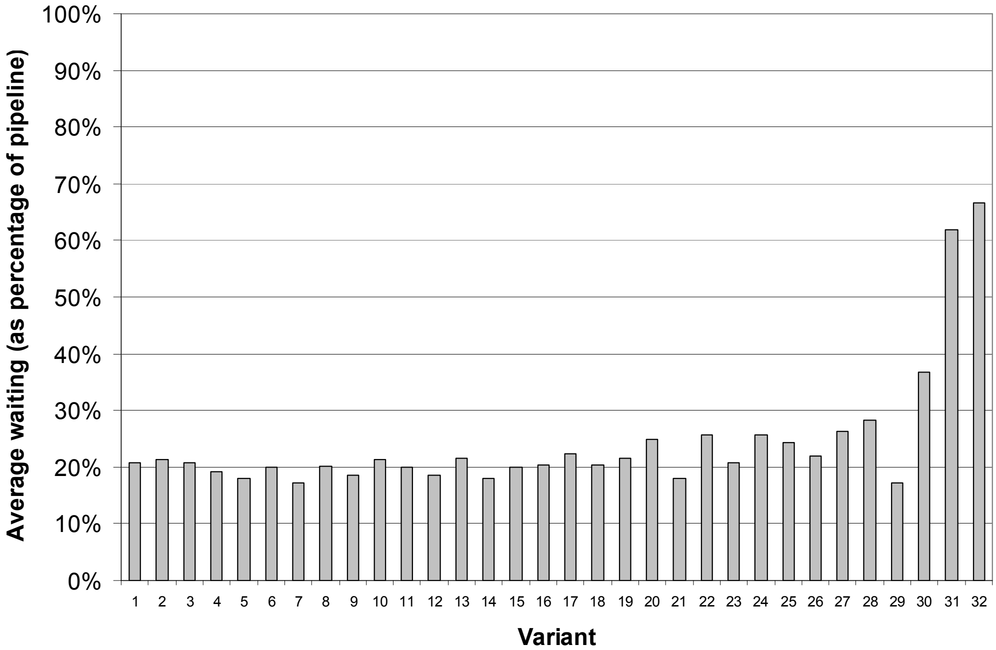


Figure 8:47 Average customer waiting time for each variant in a Conventional system (skew 70/30, variety 32)



8.4.4 Reconfiguration flexibility

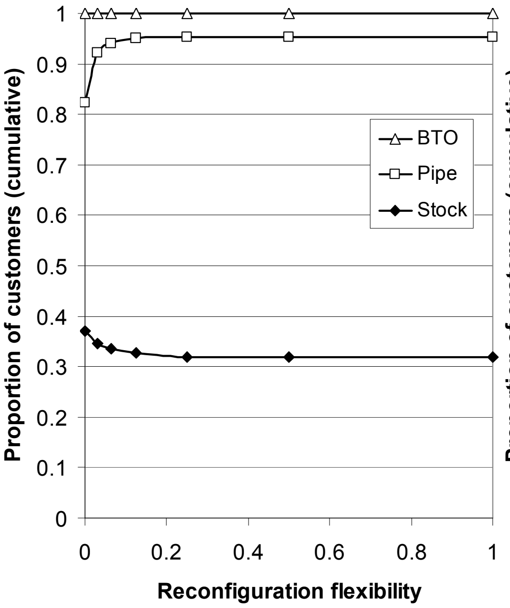
From the earlier study of the pipeline in isolation, it is known that reconfiguration flexibility leads to substantial benefits in terms of finding a suitable product in the pipeline (section 8.3.3, page 75). This section shows that the benefits obtained from flexibility in the pipeline are moderated by the other mechanisms.

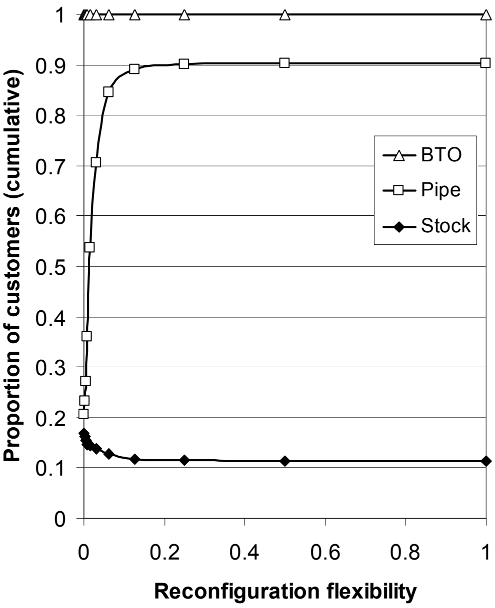
One pipeline length is studied (128) at two variety levels (32 and 512, hence the two variety / pipeline ratios studied are 0.25 and 4) and reconfiguration flexibility[17] is increased from 0 to 1.

As shown in the two graphs of Figure 8:48, while there is a substantial increase in the fulfilment from the pipeline as the reconfiguration flexibility increases, it does not eliminate the other forms of fulfilment. The results show that a small amount of reconfiguration can have a dramatic impact on the fulfilment mechanism and that there is a diminishing return from increasing flexibility.

Although the proportion of customers that wait the entire pipeline length (i.e. for BTO products) decreases, the impact on average waiting time as flexibility is raised is complex as shown in Figure 8:49. As flexibility increases, customers tend to be fulfilled from upstream in the pipeline. This is illustrated by the graphs in Figure 8:50, which plot from where along the pipeline customers are fulfilled[18]. At zero reconfiguration flexibility only a few customers are fulfilled from the pipeline and they are distributed evenly along the pipeline. As reconfiguration flexibility increases, more customers are fulfilled from the pipeline and they are biased to the upstream end (since more and more products in the downstream part of the pipeline are allocated already to customers).

Figure 8:48 Fulfilment by mechanisms at a range of reconfiguration flexibility levels (Cumulative plot, backward search, closest specification, pipe 128, variety 32 left graph, variety 512 right graph)





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[17] Reconfiguration flexibility is converted into a fraction, e.g. flexibility of +/- 20 in a product range of 100, gives a flexibility fraction of +/- 0.2. A flexibility fraction of 1 means that a variant can be converted into any other variant.

[18] The plots are each from single runs of 20,000 customers with the first 4000 discarded.

Figure 8:49 **Average Customer waiting time (Backward search, closest specification, pipe 128, variety 32 left graph, variety 512 right graph)**

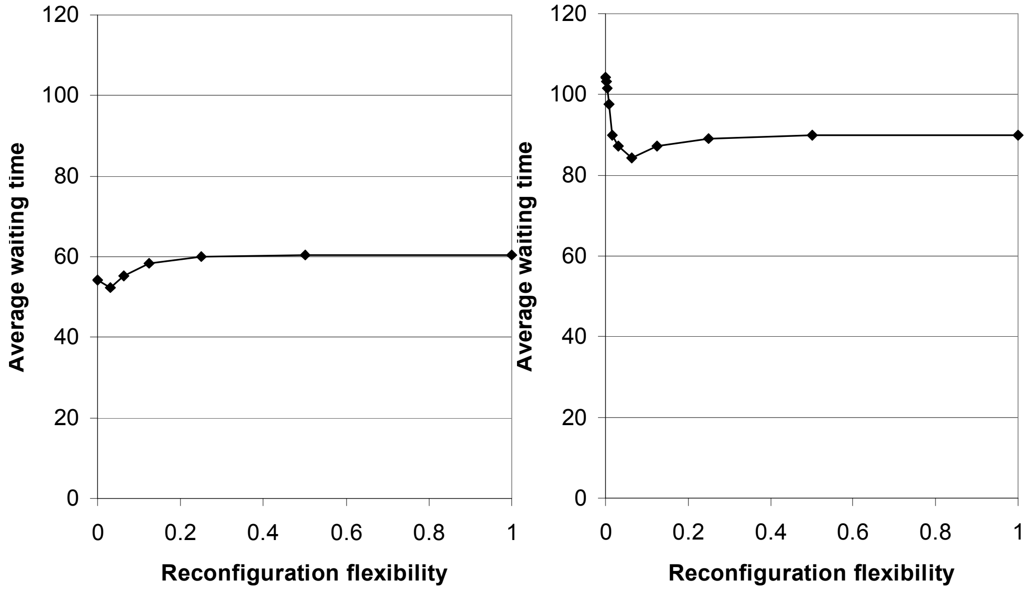
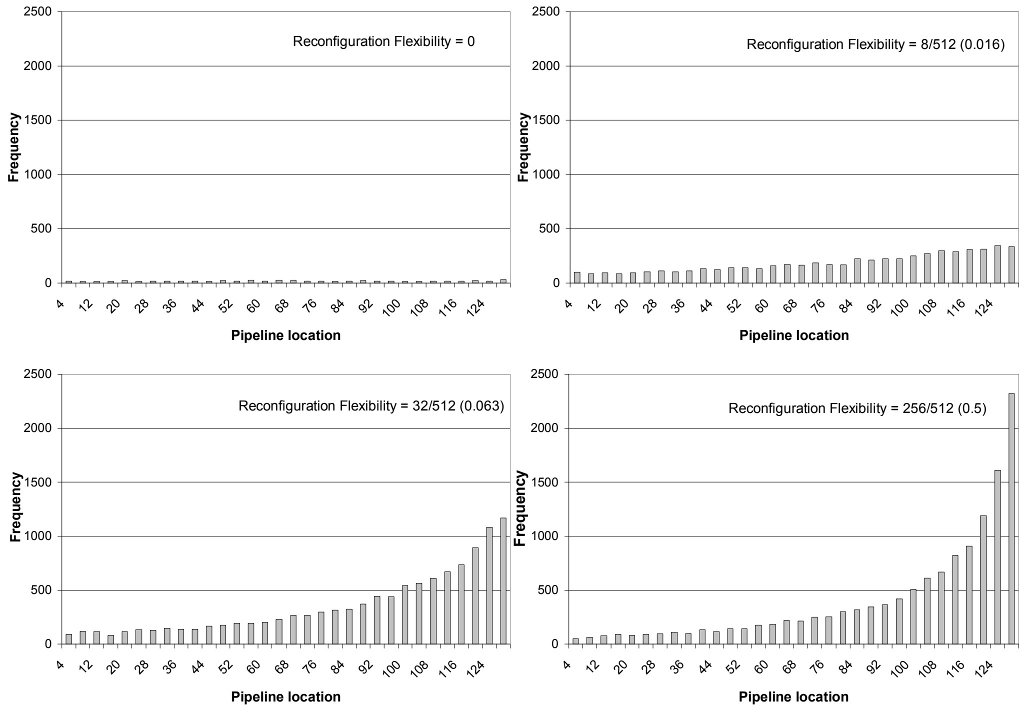


Figure 8:50 **Frequency distribution of the pipeline location from where products are allocated to customers, at four levels of reconfiguration flexibility (Backward search, closest specification, pipe 128, variety 512)**



8.4.5 Customer compromise

The concept of customer compromise may be viewed as very nearly the reverse of reconfiguration flexibility - rather than the specification of products being changed it is customers who accept a change in specification from their initial request. Just as reconfiguration flexibility can be one-way or two-way, customers can be modelled as compromising one-way or two-way. In this study it is one-way downward compromise that is modelled. Consider a customer seeking a product with the specification 27 who is prepared to compromise by a maximum of 3 steps. In one-way downward compromise they can be fulfilled by a 27, 26, 25 or 24.

There are two notable differences between customer compromise and reconfiguration flexibility. The first is that when customers compromise they can be flexible in which products they take from stock as well as from the pipeline, whereas reconfiguration flexibility is, for obvious reasons, restricted to the pipeline. This leads to stock having a greater role in fulfilling compromising customers, as shown in Figure 8:51 which can be compared to the right-hand graphs in Figure 8:48 and Figure 8:49[19]. A conclusion that follows is that if products in stock could be reconfigured to the same degree as in the pipeline, then reconfiguration flexibility and customer compromise would be equivalent.

Average customer waiting time is impacted more by customer compromise than by reconfiguration flexibility because more are fulfilled from stock. Customers that are fulfilled from the pipeline are distributed along the pipeline in a similar pattern as observed above but fewer customers are fulfilled from the pipeline (comparing Figure 8:52 to Figure 8:50). Figure 8:53 compares how introducing 100% flexibility or 100% compromise alters the average customer waiting time (compared to no flexibility or compromise) and shows that at higher variety levels, customer compromise has over double the effect.

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[19] Customer compromise is expressed as a fraction in just the same way as reconfiguration flexibility, e.g. compromise of +/- 20 in a product range of 100, gives a compromise fraction of +/- 0.2. A compromise fraction of 1 means that a customer will accept any other variant.

Figure 8:51 Fulfilment by mechanism and Average Waiting time for increasing levels of customer compromise (Backward search, closest specification, pipe 128, variety 512)

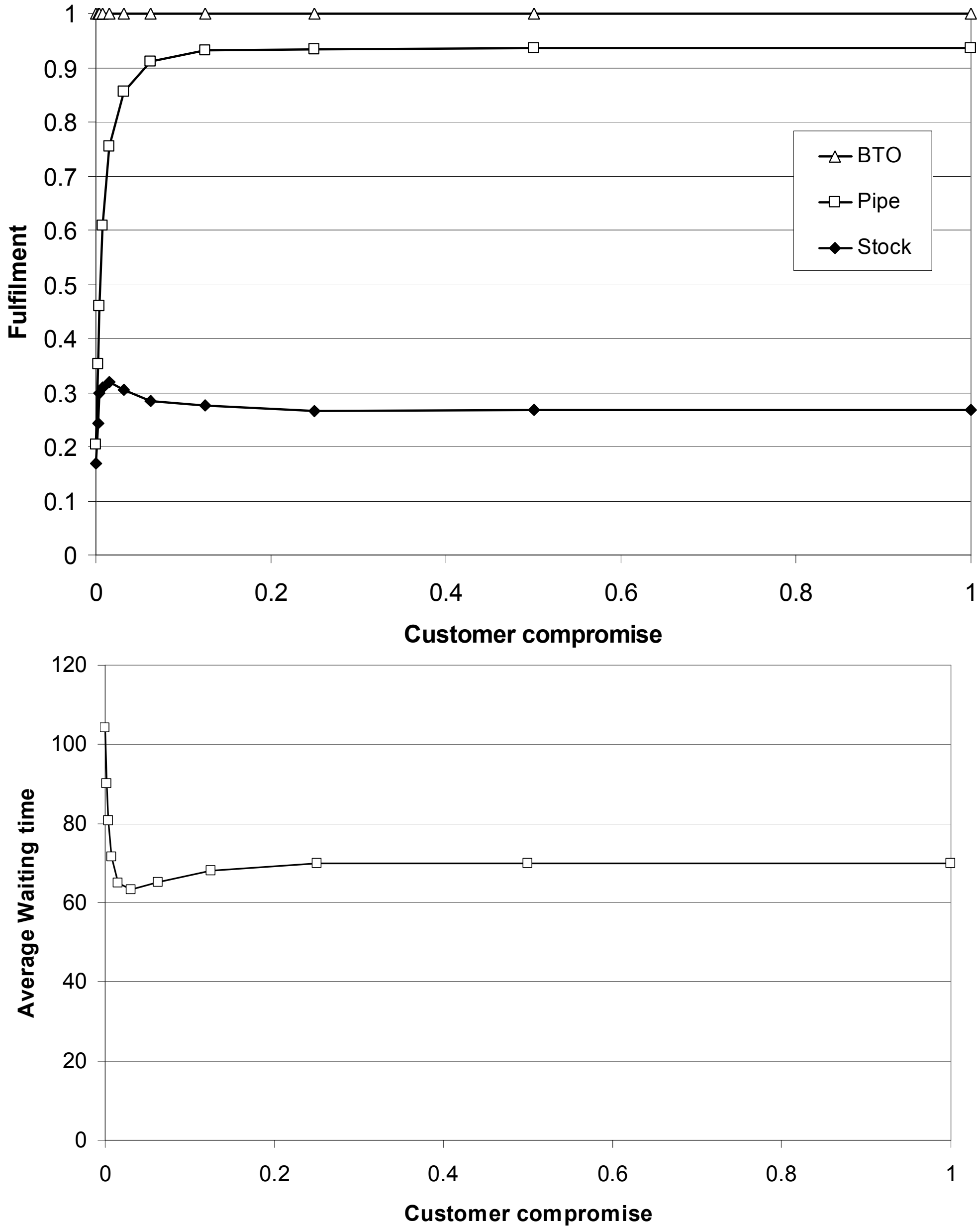


Figure 8:52 Frequency distribution of the pipeline location from where products are allocated to customers, at two levels of one-way compromise (Backward search, closest specification, pipe 128, variety 512)

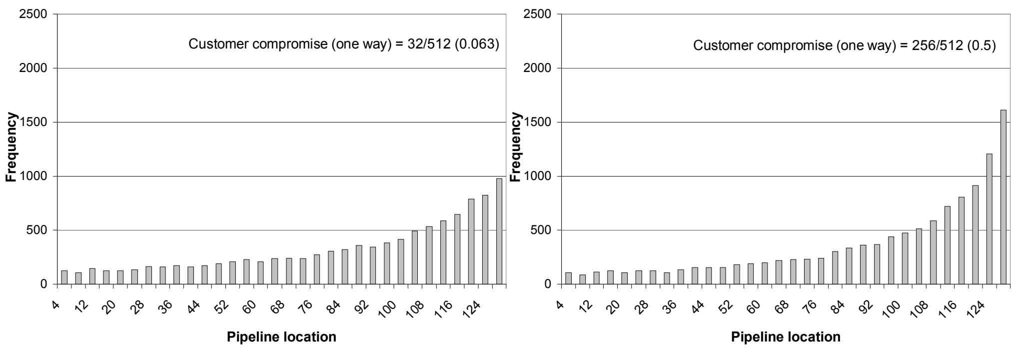
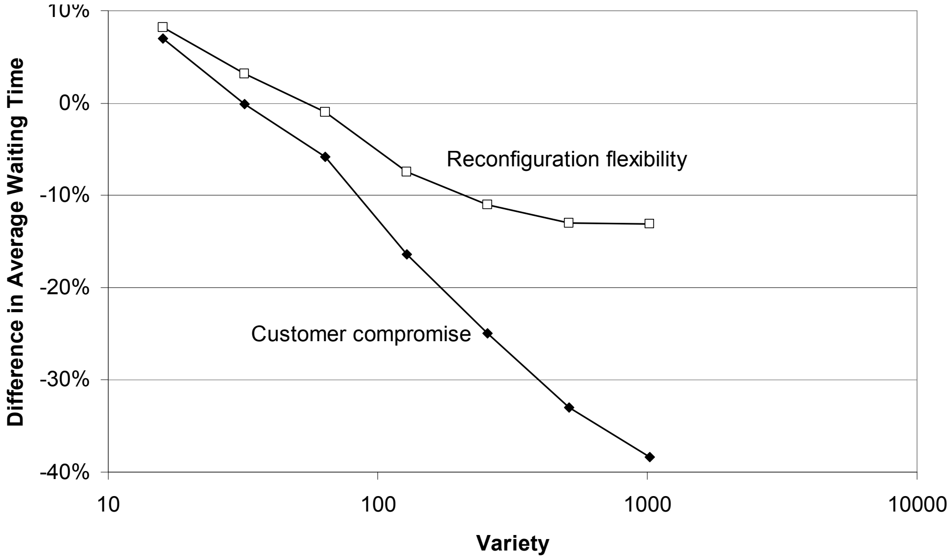
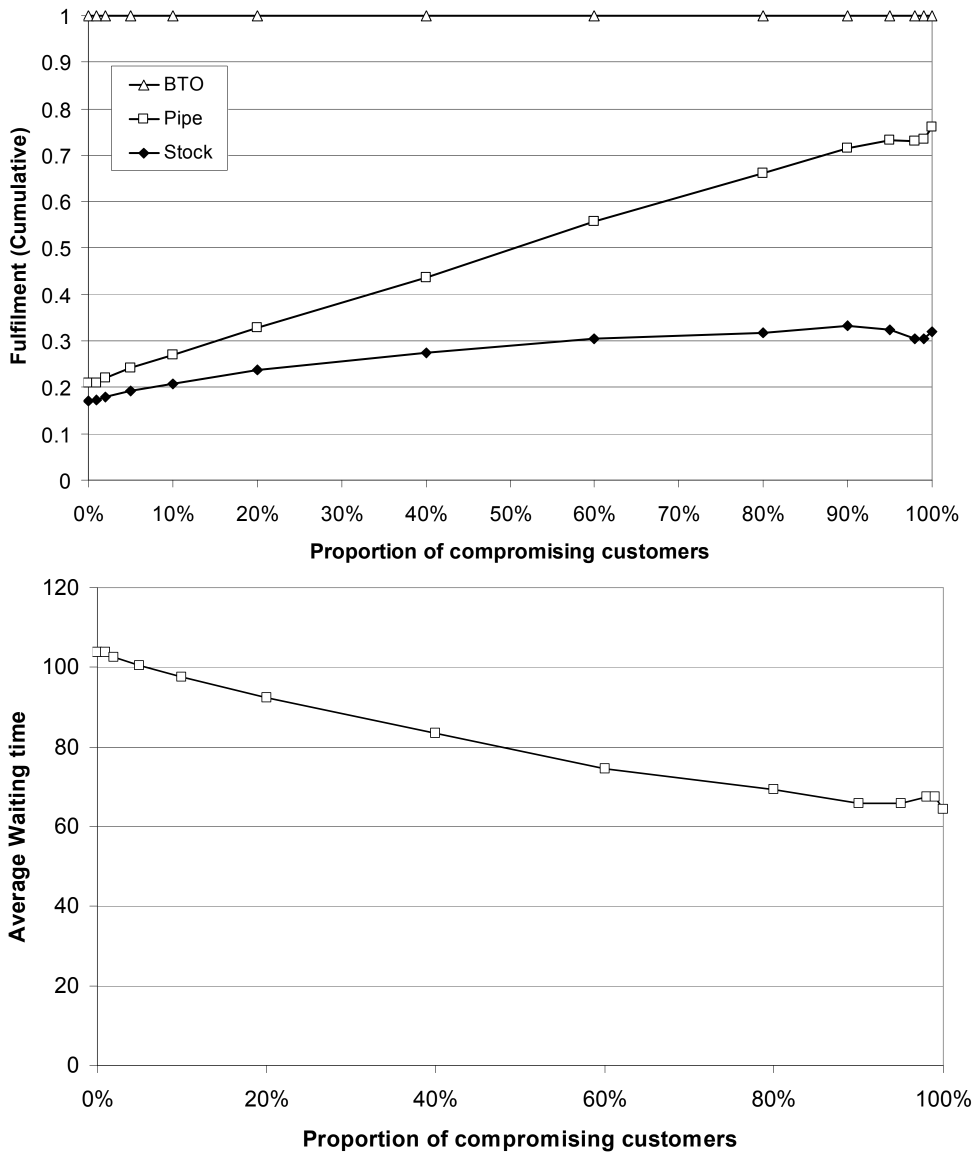


Figure 8:53 Difference in Average Customer Waiting time when comparing zero reconfiguration flexibility or customer compromise to 100% reconfiguration flexibility and 100% customer compromise



The second notable difference between customer compromise and reconfiguration flexibility is that segments of the customer population can have different tolerances to compromise. The graphs of Figure 8:54 study the impact of a mix of two customer types. One type will not compromise in specification but the other will. The issue of segmenting the customer population is studied in the next chapter.

Figure 8:54 Fulfilment by mechanism and Average Waiting time for a mix of two customer types – one accepting no compromise, the other accepting 8/512 compromise (Backward search, closest specification, pipe 128, variety 512)



8.5 Discussion

The VBTO system has been studied at different levels of complexity, firstly as a pipeline of products and a sequence of customers, then as a system with stock and BTO fulfilment. The objective has been to study the system in respect of how fundamental endogenous characteristics of the system (i.e. product variety, pipeline length, and reconfiguration flexibility) and fundamental exogenous factors (i.e. customer compromise and customer mix) affect fulfilment, and how the VBTO system compares to the Conventional system with an invisible pipeline..

Under most conditions, the relationship between fulfilment mechanism and the non-dimensional measure of product variety / pipeline length is a predictive quantitative relationship and is a primary determinant of fulfilment behaviour. The results in Phase 1, in which the pipeline was studied in isolation, indicate the variety/pipeline ratio to be reliable under conditions of uniform product variety and when reconfiguration flexibility is introduced. It also shows a consistent pattern of divergence from the uniform case as the variety distributions become skewed, but the ratio is still a major influence. The ratio is also reliable for predicting the behaviour of the full three mechanism VBTO system.

The ability to reconfigure products while in the pipeline is powerful. It allows the producer to achieve equivalent fulfilment performance with a shorter pipeline and hence reduces customer waiting times. However, the introduction of flexibility into the pipeline adds more complexity to behaviour of the system, since the pipeline section is effectively operating at a different level of variety to the stock section. Customer compromise is equivalent to the pipeline and stock operating at a reduced level of variety.

By studying the VBTO system without the inclusion of feedback mechanisms (such as the feed of products into the pipeline being dependent on previous customer orders), fundamental system behaviours have been identified. The unexpected finding that at low to medium variety/pipeline ratios, stock levels in the VBTO system are higher than in the Conventional system is a case in point. By giving access to the pipeline and therefore having more products available to customers, it is counter intuitive to expect the level of stock to be significantly higher than in a Conventional system operating under the same conditions. The explanation of this has been found to lie in the interaction of the customer and pipeline sequences resulting in the pipeline stripping phenomenon and confirms the VBTO system to be complex and meriting study.

The final section of this chapter brought in the aspect of customer segmentation by noting that not all customers can be assumed to have the same tolerances to compromise. The implications of customer segmentation for the order fulfilment system is a fertile area for research and is studied in the next chapters.

8.5.1 Implications for a producer

This research has insights and raises questions of importance to a producer. A very important finding is that opening the pipeline changes the behaviour of the system. Two key insights are:

- No longer is it a case of customers being fulfilled either from stock or by BTO, in which there are two waiting times only. Instead, a customer could wait any length of time up to the length of the pipeline and a customer will only find out how long their wait will be when the system is searched.
- Stock in a VBTO system can not be monitored in the same way as in a Conventional system. In the Conventional closed pipeline system, the mix of stock can be used as an indicator of whether production and demand are in harmony. This is no longer a valid indicator in the VBTO system.

A producer can use flexibility in the pipeline to reduce the role of stock. However, their customers may have to wait longer (see Figure 8:49, page 101). One of the attractions of the VBTO model is that there are several fulfilment modes, and customers who want a product in short lead time and are prepared to compromise on the specification can find an adequate product in stock. If a producer uses flexibility in the pipeline the stock level will be reduced and could harm this customer segment. This raises questions of how the pipeline is managed, such as whether a fraction of the pipeline should be kept invisible in order to sustain stock.

Chapter 9
Reconfiguration flexibility and customer differences

Abstract

The customer population is segmented, with each segment having different attitudes to how much compromise they will accept from their target specification. The implications of this form of segmentation on fulfilment performance are studied by varying the proportions of each segment in the customer mix. To facilitate this investigation the product is modelled in more detail as constituting four features which are independent in terms of reconfiguration flexibility. It is observed that customer mix does have a significant bearing on fulfilment – increasing the proportion of customers that are willing to compromise leads to a higher proportion being fulfilled from stock and the pipeline. Increasing the ability to reconfigure products reduces the sensitivity to customer differences. Several factors under the control of the producer are investigated, including the product mix fed into the pipeline, rules for searching for a product on behalf of a customer, and whether reconfiguration flexibility is spread across all features or focused in one feature.

9.1 Introduction

In this chapter the modelling of the product and of customer behaviour is developed further in order to investigate in depth the fulfilment implications of reconfiguration flexibility in the pipeline and flexibility in the customer population.

Products are modelled as having a modular architecture, with four features (A, B, C and D). Each feature has five options (1 - 5), giving a total of 625 product variants[20]. In terms of the fulfilment process, this structure allows reconfiguration flexibility to be different for each feature, e.g. one feature can be modelled as being reconfigurable into any option, while another feature may have less or no flexibility.

Every customer is seeking a target specification, i.e. one of the 625 variants, but a customer is assumed to treat each feature as being either *critical* or *non-critical:*

- a critical feature is one for which the customer must receive their target option;
- the customer will tolerate an alternative option for a non-critical feature.

For some customers all four features will be critical, but for others only three, two, or just one feature will be critical. The proportion of each type of customer in the population is varied, revealing the sensitivity of fulfilment metrics to the mix.

A further aspect of feature criticality that is investigated is whether the customers rank the features in the same order. In *random criticality* there is no consensus amongst customers about which features are critical, hence for one customer features A and D may be critical while for another customer who also has two critical features it may be features B and C. The alternative situation is *common criticality*, in which case: all customers treat feature A as critical; those customers who consider two or more features as critical will treat B as critical also; for those with three or more critical features then C will also be critical; hence D is critical only for those customers who consider all four features to be critical.

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[20] A variant is a unique combination of the options: A1-B1-C1-D1; A1-B1-C1-D2; ....; A5-B5-C5-D5.

In this chapter other nuances of the fulfilment system and customer behaviour are examined also. In regard to non-critical features, customers are modelled either as being willing to have any other option, or they are modelled as accepting only an option that is an upgrade to their target option. The former is equivalent to the customer being prepared to compromise, and the latter is identical to the customer accepting only substitutions[21]. In regard to reconfiguration flexibility, the system is modelled as either being able to reconfigure upwards and downwards (i.e. two-way), or upwards only (i.e. one-way, which is identical to a substitution policy). This is explained further when it is first analysed in section 9.4 on page 125.

The questions addressed in this study are:

- What is the effect on fulfilment metrics of reconfiguration flexibility in conditions of a mixed customer population?
- Are there differences in fulfilment when the customer population exhibits common and random criticality?
- Can the producer alter fulfilment performance by changing the mix of products being fed into the pipeline, or by altering the search rules?

9.2 Approach

9.2.1 Model

The model of the VBTO system is identical in structure to the model described in Chapter 8 with three fulfilment mechanisms: stock, pipeline and BTO. In this study a backwards search is used only, hence stock is searched first, then the pipe and if no suitable product is found a BTO request is submitted.

9.2.2 Customer mix scenarios

Customers are divided into four types – those that have <u>one</u> critical feature (and three non-critical), those that have <u>two</u>, those that have <u>three</u> and those that have <u>four</u> critical features. The proportion of customers of each type is varied, with nine scenarios presented in the table below.

Table 9:1 Proportion of each customer type in 9 population scenarios

Scenario	Type 4 1 feature is critical	Type 3 2 features are critical	Type 2 3 features are critical	Type 1 4 features are critical
1	-	-	-	100 %
2	-	-	100 %	-
3	-	100 %	-	-
4	100 %	-	-	-
5	60 %	25 %	10 %	5 %
6	10 %	60 %	25 %	5 %
7	5 %	25 %	60 %	10 %
8	5 %	10 %	25 %	60 %
9	25%	25%	25%	25%

[21] The acceptance of any other option for a feature is identical to two-way compromise as described in Chapter 8. The acceptance of options that are above their target is identical to one-way compromise as described in Chapter 8.

9.2.3 System variables

A single variety/pipeline condition is studied. The variety is 625 and the pipeline length is 300 which equates to a variety/pipeline ratio of 2.1 approximately. Under these conditions 10% of customers would find an exact match in the pipeline if there were no reconfiguration flexibility using a backwards search, 24% would be fulfilled from stock and 66% would be fulfilled by the BTO mechanism (see Figure 8:19, page 81). This variety / pipeline ratio is appropriate therefore to reveal if the customer segmentation studied here has a bearing on pipeline fulfilment in particular.

Extrapolating the findings to other variety /pipeline ratios is discussed at the end of the chapter.

The production rate is fixed at one product per time period. Customer arrival rate is constant and equal to the production rate.

The sequence of products fed into the pipeline is random with all 625 variants having equal probability in the default case. The sequence of specifications demanded by customers is also random and the default case is for all 625 variants to have equal probability in production and in demand.

9.2.4 Performance metrics

The metrics of interest are:

- proportions of customers fulfilled via each of the three mechanisms – stock, pipe and BTO;
- proportion of customers receiving a product that fully matches their critical and non-critical features;
- proportion of customers receiving a product that matches their critical choices but deviates on some or all of their non-critical features;
- proportion of customers fulfilled by a reconfigured product;
- customer waiting time. The unit of time in this study is the time between products entering the pipeline. The production rate is fixed, therefore in n time periods, n products enter (and leave) the pipeline;
- amount of stock.

9.2.5 Study stages

The study is divided into three main stages.

The first stage examines the behaviour of a VBTO system that has no reconfiguration flexibility in a random-criticality customer environment. Two rules for searching for a product are tested and the implications of customers either being willing to compromise or accepting substitutions is examined.

In the second stage the implications of reconfiguration flexibility is explored. Flexibility is introduced gradually in two ways, in one it is spread across all product features and in the other it is focused on one feature.

In the third stage of the study the environment is switched to common-criticality. The results are compared to the earlier stages, with and without reconfiguration flexibility. Table 9:2 summarises the experimental conditions analysed in the sections of this chapter. Definitions of the parameters, such as search methods and pipeline feed are explained in the text of the chapter.

Table 9:2 Summary of experimental conditions

Section	Customer Criticality	Customer Compromise	Reconfiguration flexibility		Search method	Pipeline feed
9.3.1	Random	Two-way	-	-	Closest	Balanced
9.3.2	Random	Two-way	-	-	First suitable	Balanced
9.3.3	Random	One-way	-	-	Closest	Balanced
9.3.3.2	Random	One-way	-	-	Closest	Skewed
9.4.1	Random	One-way	Spread	One-way	Closest	Balanced
9.4.2	Random	One-way	Spread	One-way	Closest	Skewed
9.4.3	Random	One-way	Spread	One-way	Substitute first	Balanced
9.4.4	Random	One-way	Focused	One-way	Closest	Balanced
9.4.5	Random	One-way	Focused	Two-way	Closest	Balanced
9.5.1	Common	One-way	-	-	Closest	Balanced
9.5.2	Common	One-way	Spread & Focused	One-way	Closest	Balanced

9.2.5.1 *Presentation of the results*

In the charts in this chapter it is the average result that is presented. In many charts a 90% confidence interval is also shown, calculated using the *t confidence interval* equation from Law & Kelton (2000):

$$\overline{X}(n) \pm t_{n-1,1-\alpha/2} \sqrt{S^2(n)/n}$$

where n is the number of observations, Xbar is the estimated mean and S is the sample standard deviation and the appropriate t-statistic is determined by the degrees of freedom and significance level.

9.3 Random criticality and no reconfiguration flexibility

9.3.1 Base-case

In the base-case the following conditions are studied:

- random criticality;
- customers accept any option for their non-critical features (full two-way compromise);
- stock and pipeline are searched for the product that has the closest specification to the customer's target (non-critical as well as critical features) and if none is found a BTO request is made. This search method minimises customer specification compromise. An alternative search method is studied later.

9.3.1.1 *Observations*

In scenario 1 (see Table 9:1) no customers compromise since only Type 1 customers are present. This makes the conditions of scenario 1 identical to those studied in section 8.4, and the proportions of customers fulfilled by each mechanism in scenario 1 should comply with those in Figure 8:17 (page 79), which is the case. Here the variety/pipeline ratio is 2.08 (625/300) and the proportions for stock-pipe-BTO are 24%-9%-67% (the first column in Figure 9:1), which is in close agreement with the 24%-10%-66% split found in section 8.4.1 (page 78) for a variety/pipeline ratio of 2.

The impact on fulfilment of an increase in customer tolerance to compromise is apparent by comparing scenarios 2, 3 and 4 to scenario 1 in Figure 9:1. There is a dramatic increase in the proportion of customers fulfilled from the pipeline. In scenario 2, in which all customers have one non-critical feature, there is a five fold increase in the proportion fulfilled from the pipeline compared to scenario 1 (from 9% to 47%, Figure 9:3). In tandem, the average waiting time drops from 217 to 132 (Figure 9:5). Increasing the number of non-critical features to 2 and to 3 (scenarios 3 & 4) eliminates the need for BTO fulfilment (Figure 9:2) and stock fulfilment is slightly higher in scenario 4 than scenario 3 (39% and 37% respectively, Figure 9:4).

These changes occur because customers are accepting compromise. When all customers tolerate compromise on one feature (scenario 2), for 51% an exact match is not available (Figure 9:7). This rises to 67% when all customers tolerate compromise on two features (scenario 3), but is no higher when all customers tolerate compromise on three features (66% in scenario 4).

Scenarios 5 to 9 look at different mixes of customer types, with scenario 5 being most weighted with customers that accept the greatest compromise (Type 4) and scenario 8 with customers that are intolerant of compromise (Type 1). Scenario 9 has equal proportion of the four customer types. From the graphs it is observed that for each type of customer the spread across the fulfilment mechanisms is sensitive to the population mix. For example, the proportions of Type 1 customers fulfilled by stock-pipe-BTO in scenario 5 are 10%-25%-66%, and in scenario 8 they are 18%-13%-69%, compared to 24%-9%-67% when all customers were type 1 (scenario 1). This pattern indicates that interactions between customer types affects the relative dominance of each fulfilment mechanism and is most clearly visible for pipe and stock fulfilment in Figure 9:3 and Figure 9:4. Indeed, pipe fulfilment is more than halved from scenarios 5 to 8 (56% to 22%).

It is observed that the customer population mix has little bearing on the proportion of customers that compromise. In Figure 9:7 the proportion per customer type varies very little from scenario to scenario. Hence it is concluded that compromise proportion is not much affected by interactions between customer types but is determined by overall system parameters e.g. variety ratio.

Average customer waiting time appears to be dependent to a small degree on population mix (Figure 9:6), less so than fulfilment mechanism but more so than compromise proportion.

Stock holding is sensitive to the population mix, and is greatest when the mix is high in non-compromising customers (scenario 8 in Figure 9:8). It is observed the pattern of stock holding and waiting time across the scenarios is near identical (Figure 9:5 and Figure 9:8), which accords with intuition as longer waiting times indicate fewer customers being fulfilled from stock.

Figure 9:1 Proportions of customers fulfilled by mechanism (Base-case, 9 population scenarios)

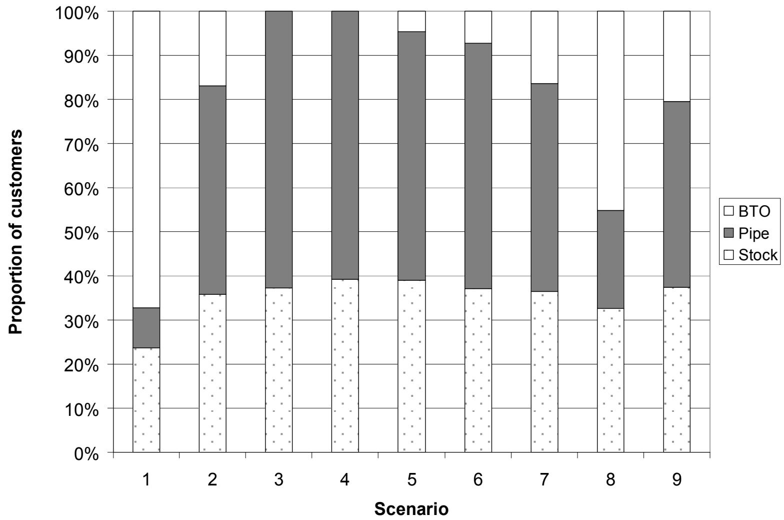


Figure 9:2 BTO fulfilment proportions for each customer type (Base-case, 9 population scenarios)

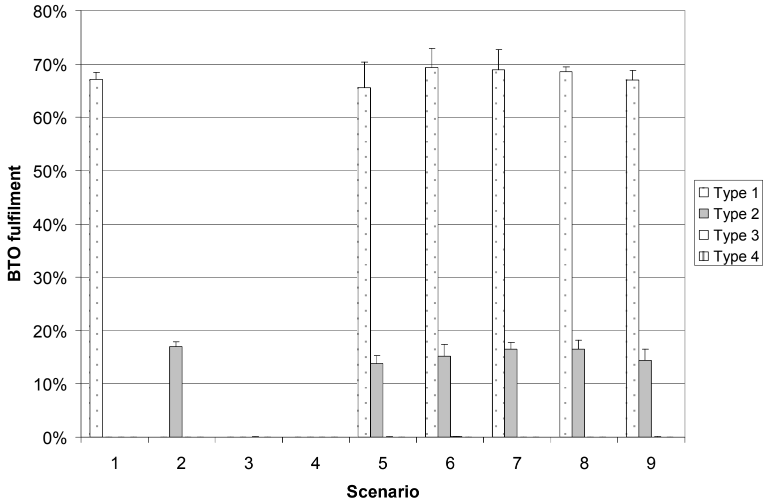


Figure 9:3 Pipe fulfilment proportions for each customer type (Base-case, 9 population scenarios)

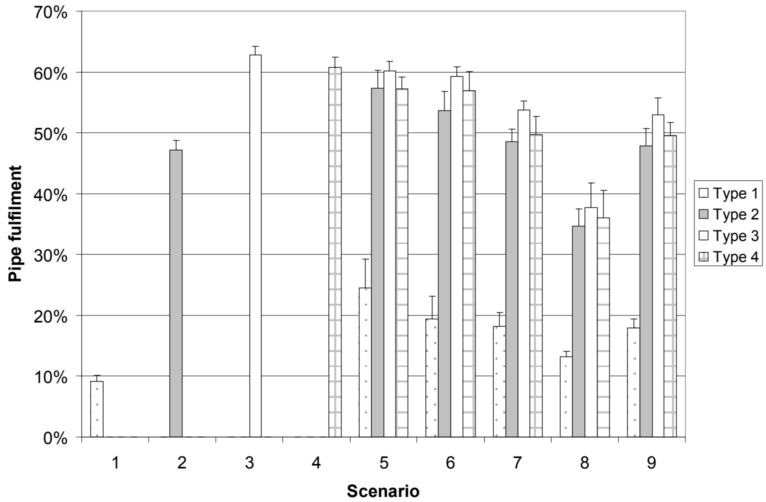


Figure 9:4 Stock fulfilment proportions for each customer type (Base-case, 9 population scenarios)

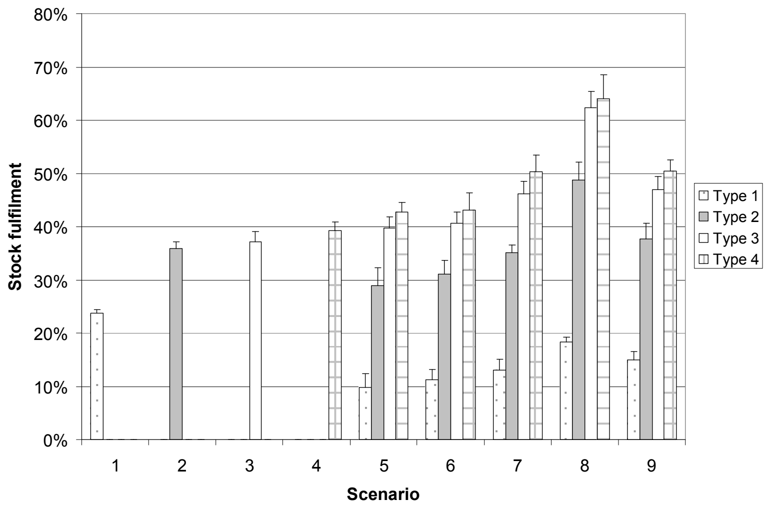


Figure 9:5 Average customer waiting times (Base-case, 9 population scenarios)

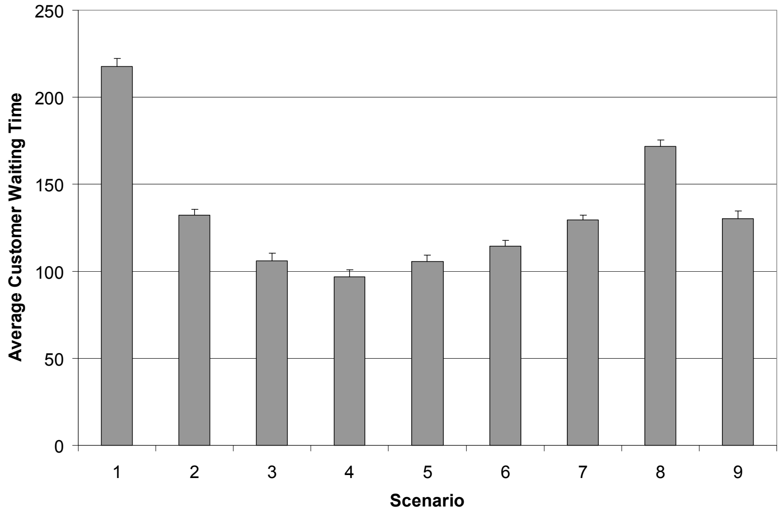


Figure 9:6 Average waiting times for each customer type (Base-case, 9 population scenarios)

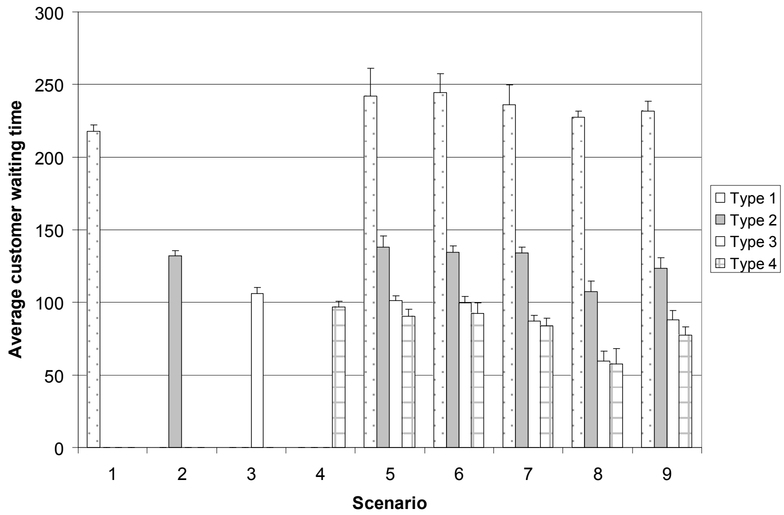


Figure 9:7 Compromising customers by type (Base-case, 9 population scenarios)

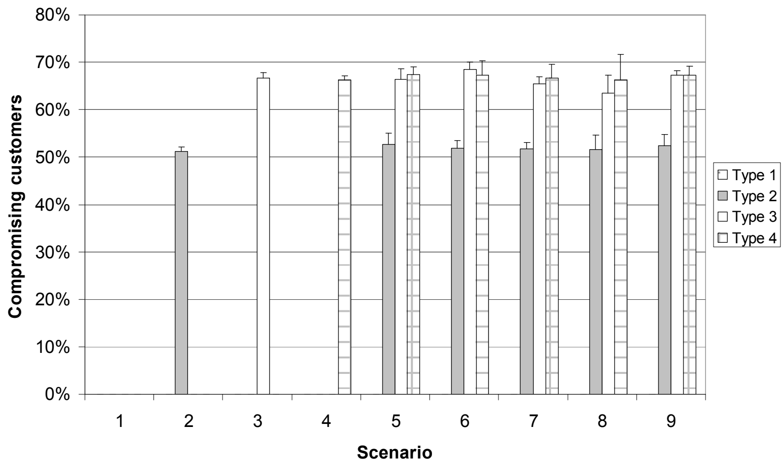
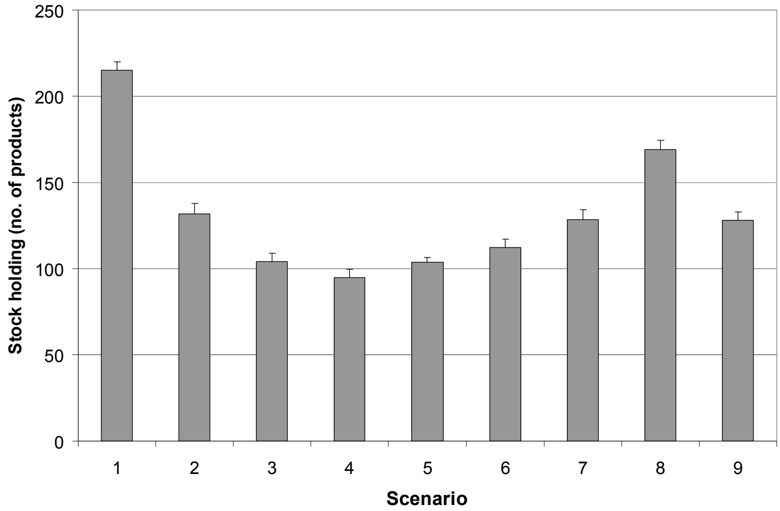


Figure 9:8 Stock holding (Base-case, 9 population scenarios)



9.3.2 Alternative search policy – first suitable product

A different search policy is implemented. Instead of stock and pipeline being searched for the product that is the *closest* match to the customer's non-critical as well as critical features, the rule is to find the first product that matches the customer's critical features. This is referred to as the *first suitable* search rule.

9.3.2.1 Observations

Across all scenarios the spread across the three fulfilment mechanisms follows the same pattern with this new search rule as for the base-case (Figure 9:9 compared to Figure 9:1). However, except when no customers will compromise (scenario 1) the role of stock is increased, evident from comparing scenarios 2, 3 & 4 in Figure 9:9 to Figure 9:1 (e.g. in scenario 4 the proportion from stock is 48% compared to 39% when using the *closest* rule).

The difference between the two search policies for the proportion of BTO customers across the scenarios is small indicating that BTO fulfilment is insensitive to policy (scenario, % difference: 1, 0.0%; 2, 5.3%; 3, 0.0%; 4, 0%; 5, 7.6%; 6, 7.7%; 7, 6.4%; 8, 1.8%; 9, 3.5%).

The proportion of customers compromising with this search rule is almost the same as for the base-case (comparing Figure 9:10 to Figure 9:7). However, this hides the fact that customers are compromising to a greater extent with this search rule than in the base-case. In the base-case, type 2, 3 and 4 customers compromised on average between 0.8 and 1 option steps[22] (Figure 9:11), whereas the average difference is between 1 and 1.4 option steps with the new rule (Figure 9:12).

With both search rules, across the scenarios the proportions of customers compromising and the specification difference are near constant, indicating that these outcomes have low dependency on mix (Figure 9:7, Figure 9:10, Figure 9:11 & Figure 9:12).

This search rule reduces average customer waiting time for customers who accept some compromise (types 2, 3 and 4, comparing Figure 9:13 to Figure 9:6 which is presented in Figure 9:14). The largest reduction is for Type 4, and is in the order of 40%. For Type 1 customers, who accept no compromise, waiting time is increased in some scenarios. It is observed that this search policy tends to result in fewer Type 1 customers being fulfilled from stock, whereas more of the other Types are (Figure 9:15).

The higher the proportion of compromising customers in the mix the more that stock holding is reduced (comparing Figure 9:16 to Figure 9:8, which is presented in Figure 9:17).

[22] With 5 options for each of the 4 features there are 16 option steps in total. I.e. the variant A1-B1-C1-D1 differs from variant A5-B5-C5-D5 by 16 steps.

Figure 9:9 Proportions of customers fulfilled by mechanism (*first suitable* search rule, 9 scenarios)

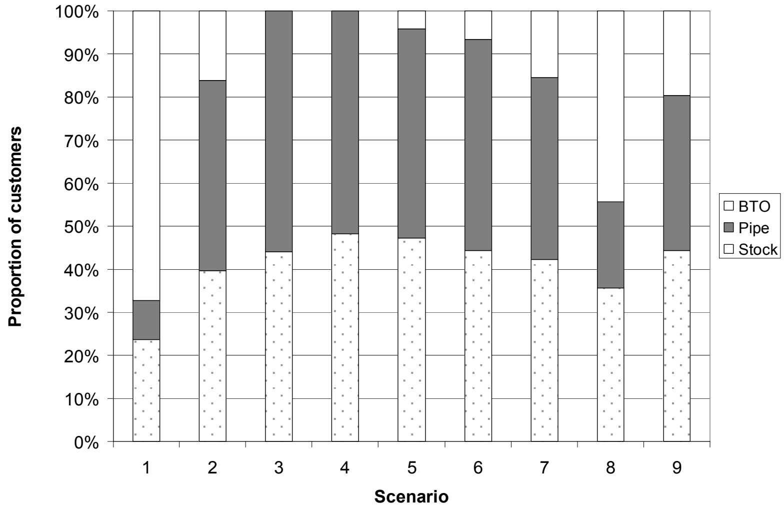


Figure 9:10 Compromising customers for each type (*first suitable* search rule, 9 scenarios)

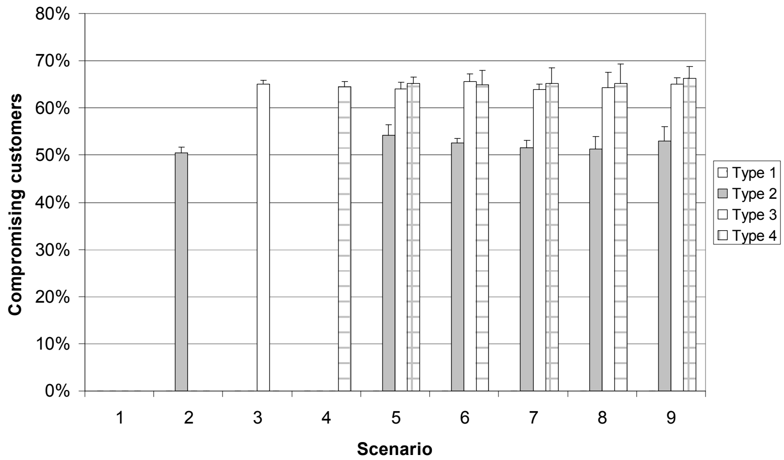


Figure 9:11 Average difference in the specification received by a customer from their target specification, measured as number of option steps (for the *closest specification* rule followed in the <u>base-case</u>)

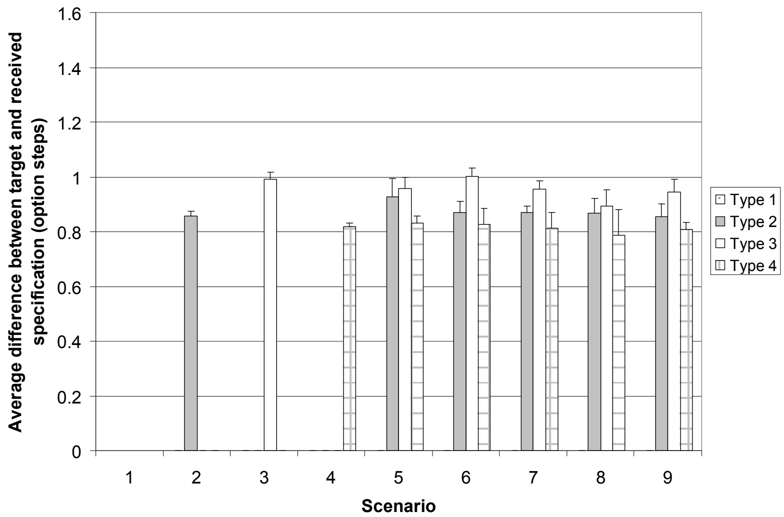


Figure 9:12 Average difference in the specification received by a customer from their target specification, measured as number of option steps (for the *first suitable product* rule)

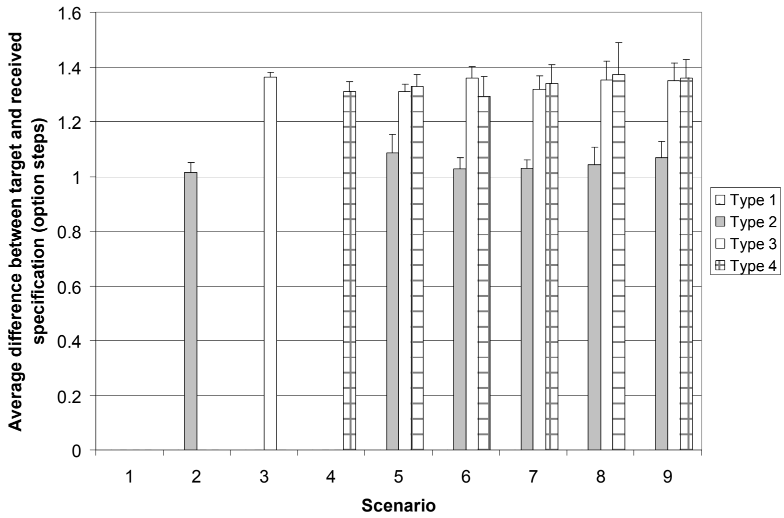


Figure 9:13 Average waiting times for each customer type (*first suitable* search rule, 9 scenarios)

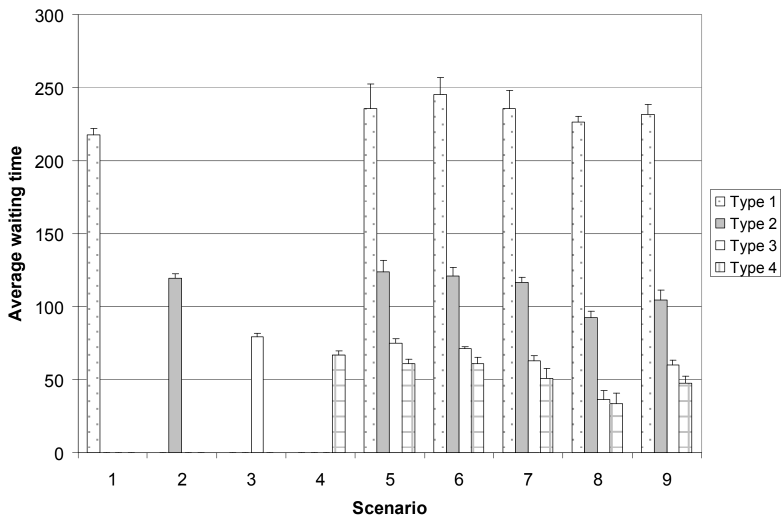


Figure 9:14 Reductions in average waiting times for each customer type between *first suitable* search rule and base-case (9 scenarios)

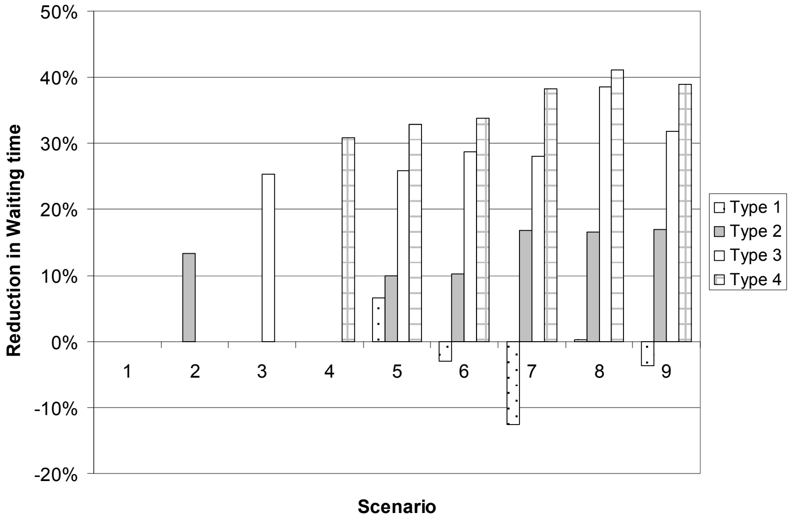


Figure 9:15 Difference in stock fulfilment for each customer type between *first suitable* search rule and base-case (9 scenarios)

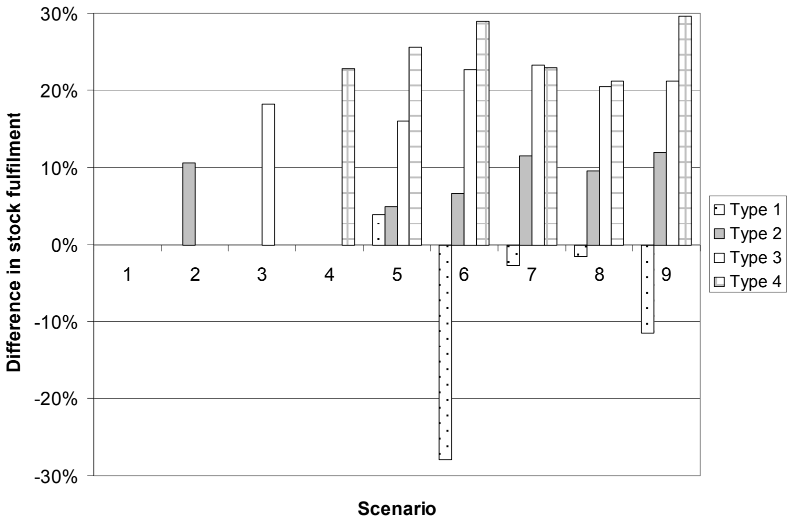


Figure 9:16 Stock holding (*first suitable* search rule, 9 scenarios)

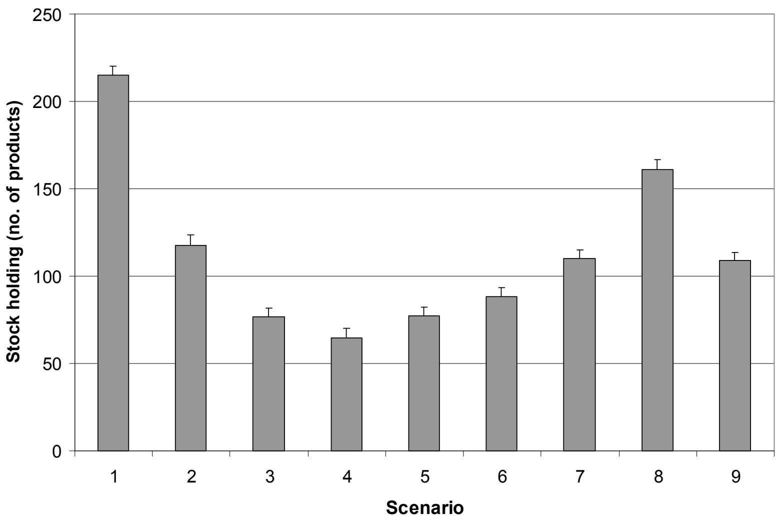
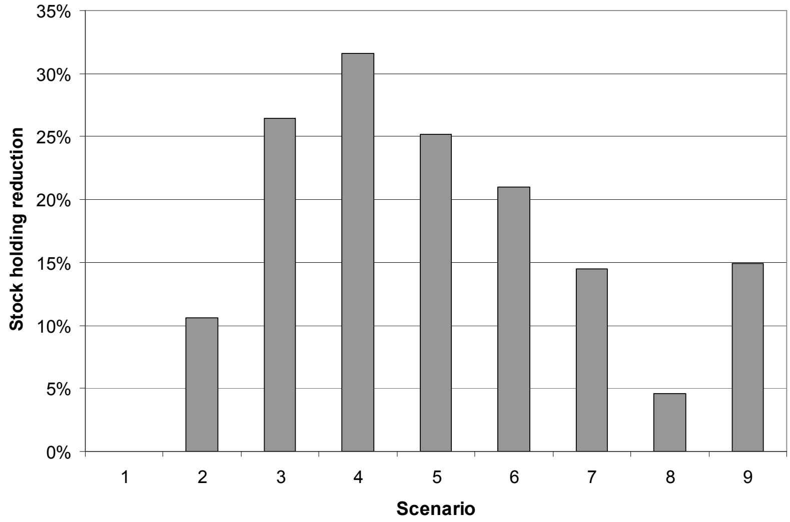


Figure 9:17 Reduction in stock holding between *first suitable* search rule and base-case (9 scenarios)



9.3.3 Alternative customer behaviour – substitution

In the base-case, customers accepted any option for a non-critical feature in the absence of an exact match, but here the rule is introduced that customers will accept only a substitution, i.e. an option which is an upgrade to their target selection. To clarify, if the options on feature B are labelled B1, B2, B3, B4 & B5, a substituting customer seeking a B4 when B is a non-critical feature, will be satisfied with a B4 or a B5. In the base-case the customer would have been satisfied with any of the 5 options.

9.3.3.1 Observations

The change in customer behaviour increases fulfilment from BTO significantly and reduces pipe fulfilment (comparing Figure 9:18 to Figure 9:1). Stock fulfilment is also reduced but to a lesser extent. It appears from Figure 9:18 that across 8 of the 9 scenarios the proportion fulfilled from stock is constant, but study of Figure 9:20 (and Figure 9:19) shows that fulfilment mechanism is sensitive to customer mix just as was observed earlier.

The drop in pipe fulfilment is down to the customers being less flexible. Fewer customers compromise than in the base-case (comparing Figure 9:21 to Figure 9:7) and it is observed that the decline is greater for the more demanding type 2 and type 3 customers than type 4 customers (Figure 9:22).

Unsurprisingly, with the shift towards BTO both the average customer waiting time and stock holding rise (Figure 9:23 and Figure 9:24 compared to Figure 9:5 and Figure 9:8). As observed above, the results for customer waiting time and stock holding are closely matched.

There is more variation in the proportion of customers substituting as customer mix changes (scenarios 5-9) than was found in the base-case (comparing Figure 9:21 to Figure 9:7).

Figure 9:18 Proportions of customers fulfilled by mechanism (substitution, 9 scenarios)

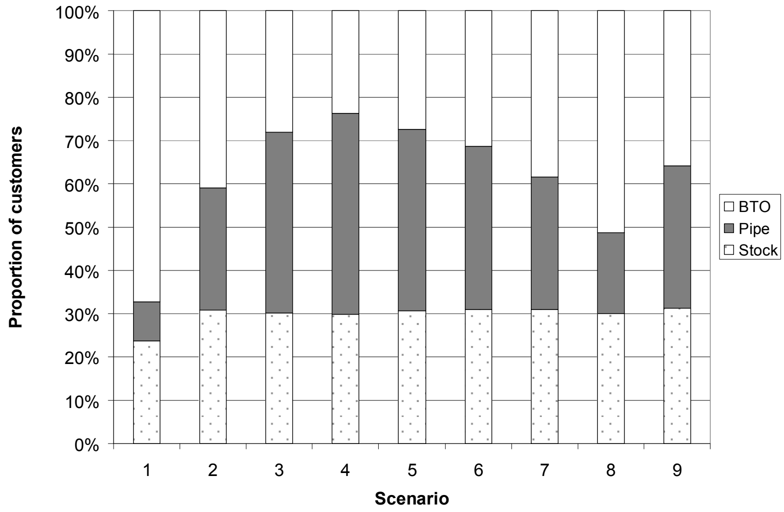


Figure 9:19 BTO fulfilment proportions for each customer type (substitution, 9 scenarios)

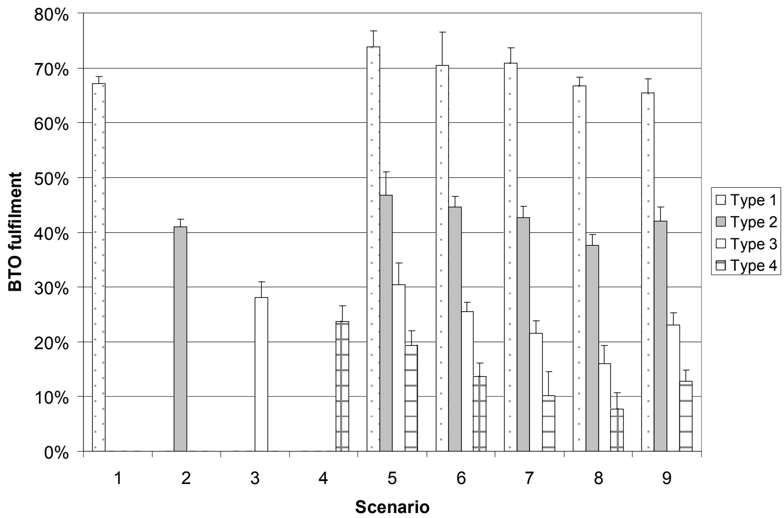


Figure 9:20 Stock fulfilment proportions for each customer type (substitution, 9 scenarios)

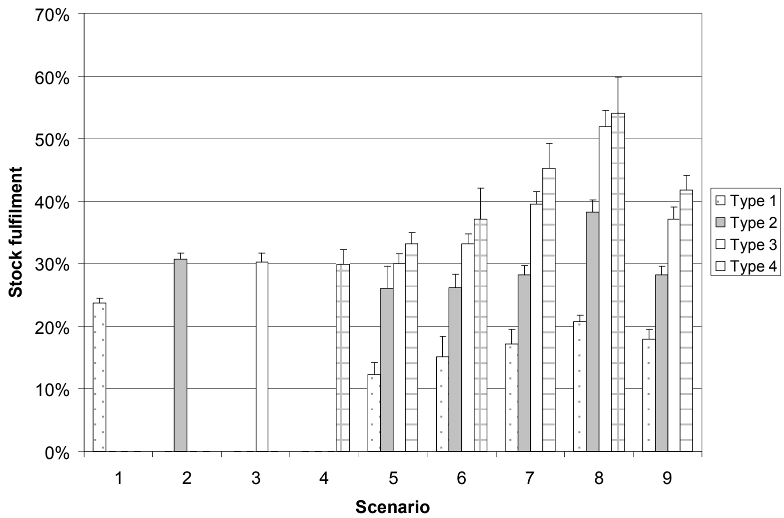


Figure 9:21 Substituting customers by type (substitution, 9 scenarios)

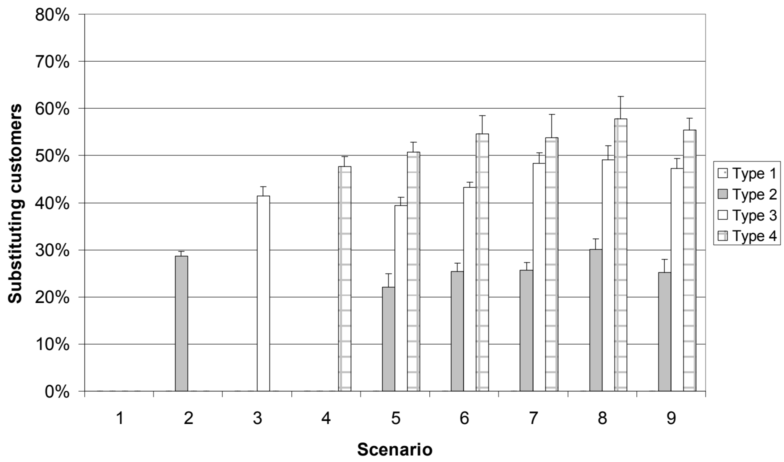


Figure 9:22 Percentage reduction in the proportion of each customer type that compromises in substitution condition compared to the base-case (9 scenarios)

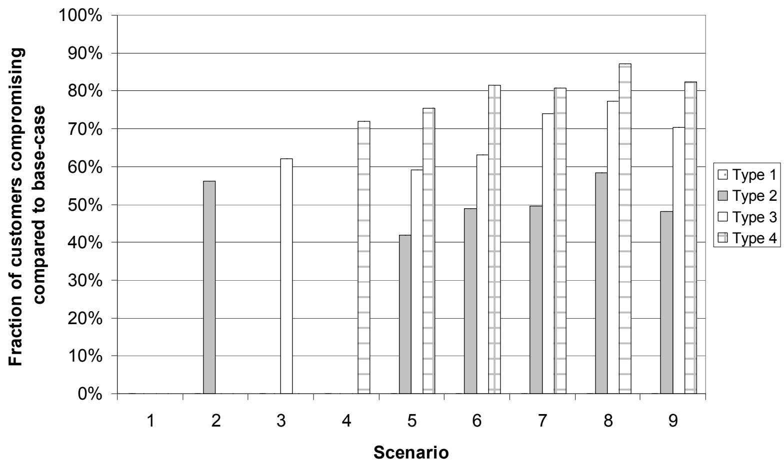


Figure 9:23 Average customer waiting times (substitution, 9 scenarios)

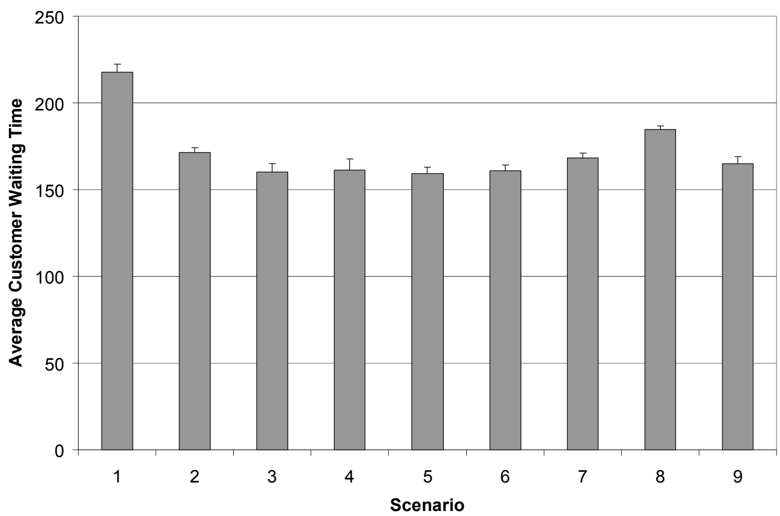
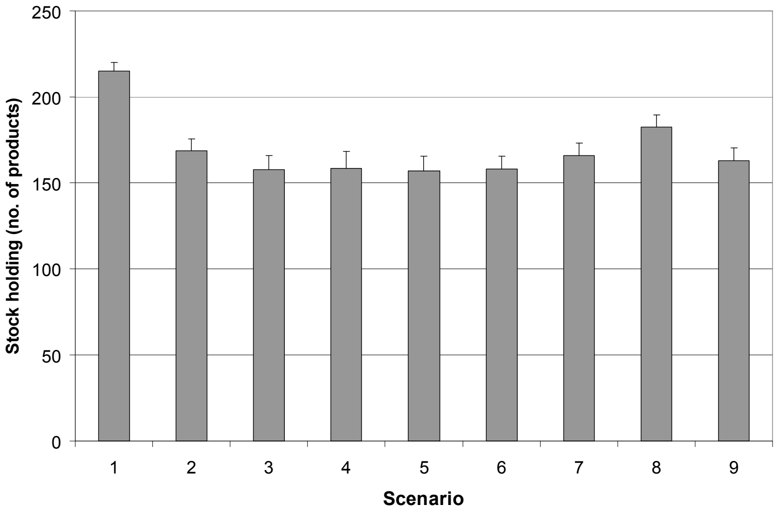


Figure 9:24 Stock holding (substitution, 9 scenarios)



9.3.3.2 *Adjusting pipeline feed distribution*

As described above, when customers accept substitutions it means they accept only options that are upgrades to their target specification. A tactic open to the producer is to adjust the proportion of each option being fed into the pipeline, skewing it such that more high-end options are available.

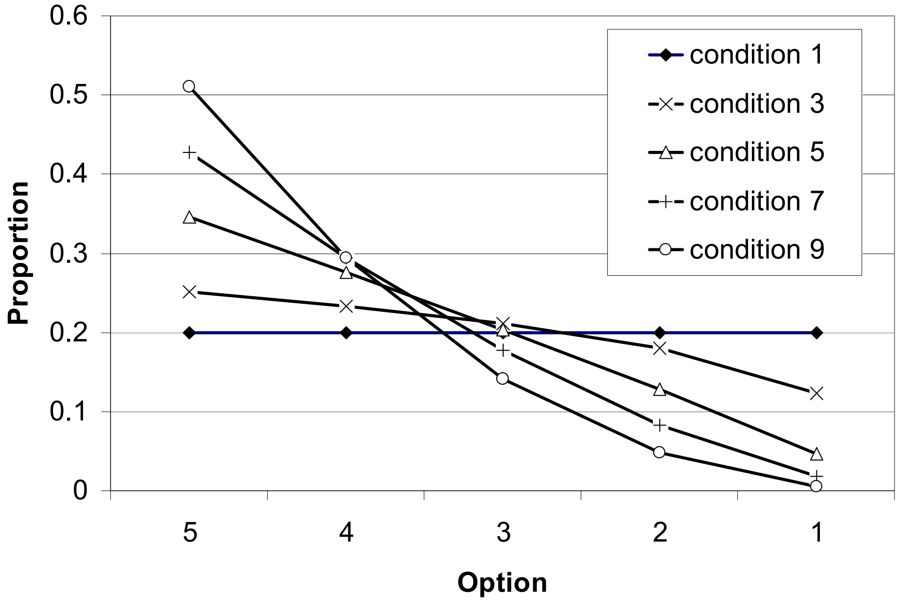
This will increase the likelihood of customers finding a suitable substitute but a downside will be that customers seeking a low-end option and not prepared to substitute will find a matching product less often. The issue to investigate is whether any level of skew can bring an overall benefit in terms of waiting time and stock levels.

To address this, nine pipeline feed distributions are compared, implemented using the Beta distribution for the substitution situation (Table 9:3 and Figure 9:25). No change is made to the customer demand distributions for options. The customer population continues to demand the 5 options of each feature in equal proportions. Two of the customer mix scenarios are examined – 5 and 8 – with scenario 5 being dominated by customers who are prepared to substitute (Type 4 customers) and scenario 8 has the inverse mix (Table 9:1).

Table 9:3 Skewed feed conditions

Skew Condition No.	Beta distribution parameters			Proportion of each option				
	Alpha	Beta	Skew	Opt.5	Opt.4	Opt.3	Opt.2	Opt.1
1	1	1	0	0.2	0.2	0.2	0.2	0.2
2	1	1.1	0.08	0.22	0.21	0.21	0.19	0.17
3	1	1.3	0.22	0.25	0.23	0.21	0.18	0.12
4	1	1.6	0.39	0.30	0.26	0.21	0.15	0.08
5	1	1.9	0.53	0.35	0.28	0.20	0.13	0.05
6	1	2.2	0.64	0.39	0.29	0.19	0.10	0.03
7	1	2.5	0.73	0.43	0.29	0.18	0.08	0.02
8	1	2.8	0.81	0.46	0.30	0.16	0.07	0.01
9	1	3.2	0.90	0.51	0.29	0.14	0.05	0.01

Figure 9:25 Illustration of the skewed feed distributions at five skew levels



Observations

The results presented in Figure 9:26 to Figure 9:29 indicate that there is scope for a producer to optimise performance by skewing the feed distribution. The impact of skew is more pronounced for Scenario 5 (Figure 9:26 and Figure 9:28) but is present also for scenario 8 (Figure 9:27 and Figure 9:29). As skew is introduced there is greater fulfilment from stock and pipe, but as it rises further, BTO fulfilment returns. Waiting time at first drops and then grows (note: stock levels are not presented since in both scenarios they are near identical to aggregated average waiting times as was observed earlier in sections 9.3.1.1 and 9.3.3.1). For Scenario 5 it is skew condition 3 that has the shortest waiting time, which is 15% less than the no skew condition (#1). For Scenario 8 it is skew condition 1 that gives the shortest waiting time, at just over 1% lower than the no skew condition (#1).

Over the skew conditions the proportion of customers being fulfilled by substitutions at first increases and then declines (Figure 9:31 and Figure 9:32).

Closer scrutiny of the four customer types in scenario 5 shows the minimum/ maximum to be at different skew levels for each customer type. For average waiting time and proportion of customers substituting, it appears that the minima/maxima are in the sequence Type 1-2-3-4 (Figure 9:30 and Figure 9:31).

Figure 9:26 Proportions of customers fulfilled by each mechanism (scenario 5 with 9 levels of skewed feed)

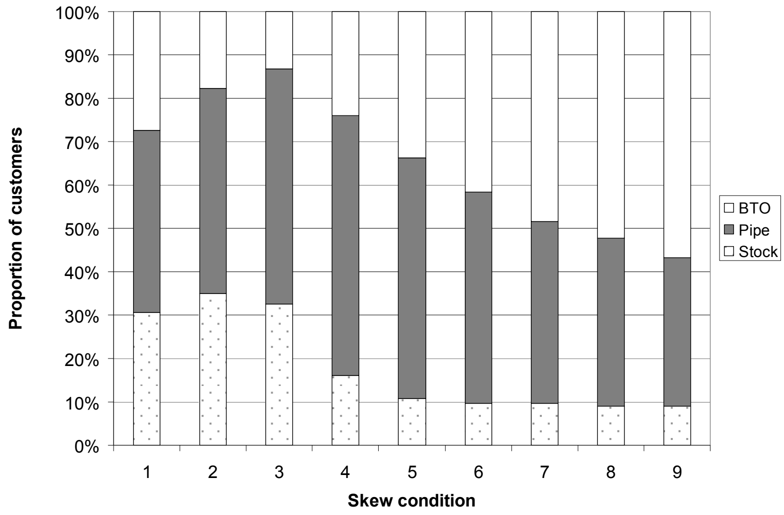


Figure 9:27 Proportions of customers fulfilled by each mechanism (scenario 8 with 9 levels of skewed feed)

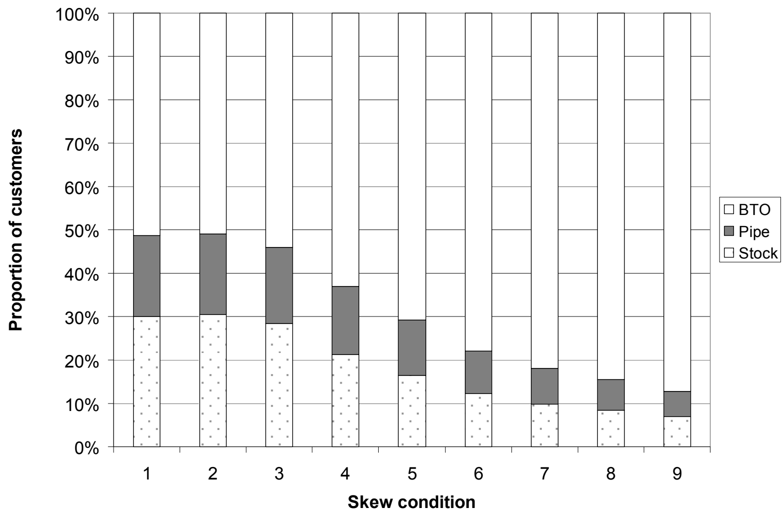


Figure 9:28 Average waiting time (scenario 5 with 9 levels of skewed feed)

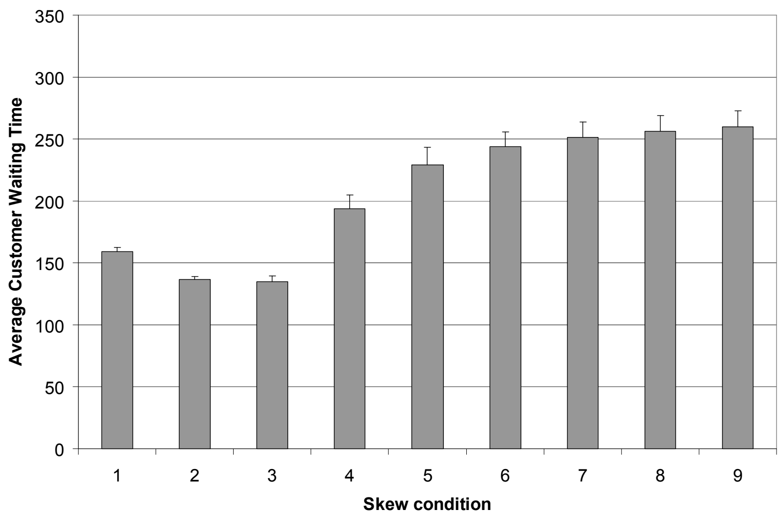


Figure 9:29 Average waiting time (scenario 8 with 9 levels of skewed feed)

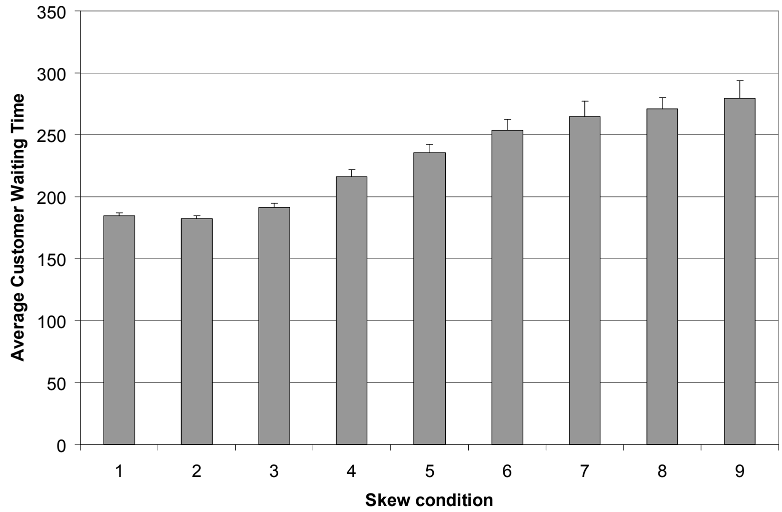


Figure 9:30 Average waiting time for each customer type (scenario 5 with 9 levels of skewed feed)

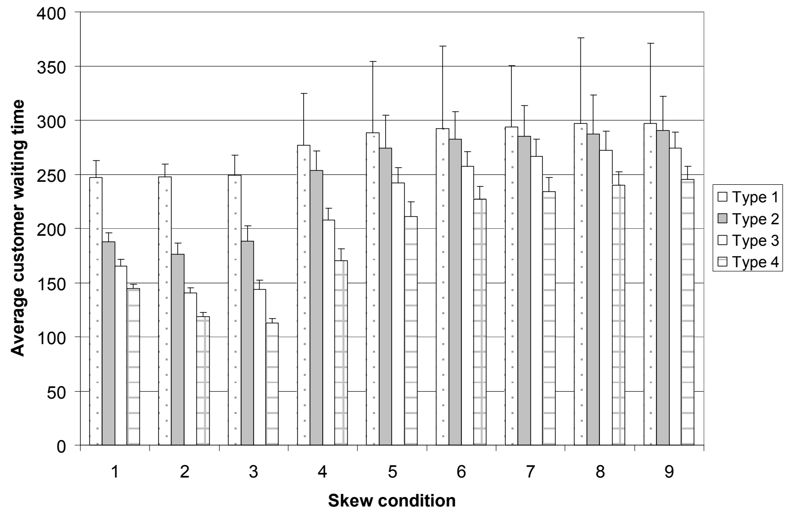


Figure 9:31 Proportion of substituting customers by customer type (scenario 5 with 9 levels of skewed feed)

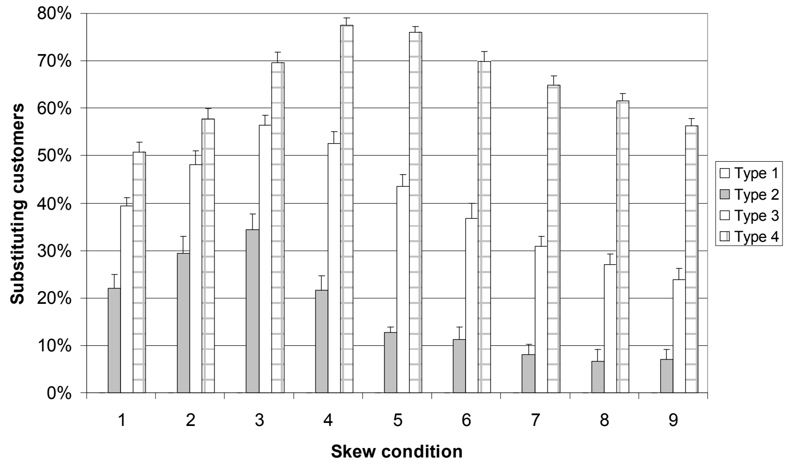
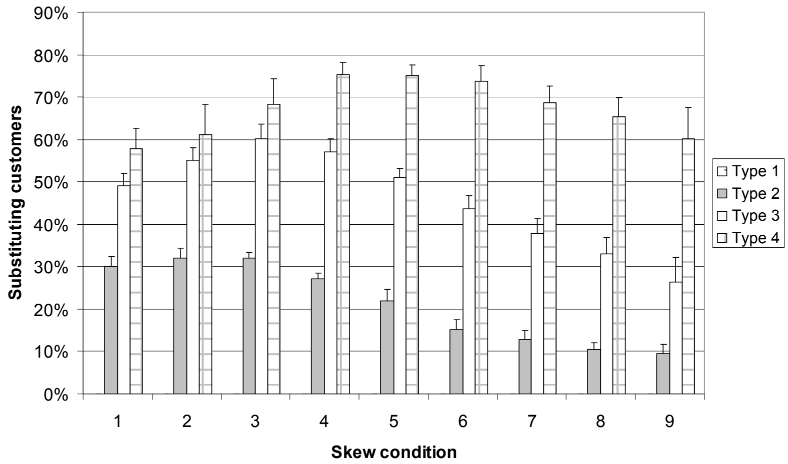


Figure 9:32 Proportion of substituting customers by customer type (scenario 8 with 9 levels of skewed feed)



9.4 Reconfiguration Flexibility

The next stage in the study is the introduction of reconfiguration flexibility. This is done in two ways in order to assess whether a producer should spread flexibility across many features or focus flexibility on one feature.

To appraise the benefit of reconfiguration flexibility, it is tested under the harshest customer conditions that have been analysed above:

- the customer mix from scenario 8 is used as this is the mix most biased toward the least flexible customers (60% of customers are type 1 for whom all 4 features are critical);
- Type 2, 3 4 customers are willing to *substitute* to a higher option on their non-critical features (i.e. they accept one-way compromise and not two-way compromise).

This study assesses the impact of *one-way upward reconfiguration flexibility*, i.e. the producer has the ability to reconfigure an option into higher options but cannot reconfigure it into lower options. To clarify, if a product enters the pipeline with a specification of A3-B5-C1-D4 and the producer is able to reconfigure up to 2 steps:

- feature A can be reconfigured into A4 or A5;
- feature B cannot be reconfigured as it is already the highest option;
- feature C can be reconfigured into C2 or C3;
- feature D can be reconfigured into D5 only.

In the VBTO system there are no limits on: the number of products passing through the system that can be reconfigured; the number of reconfigurations into or away from an option; or any constraints on the location of reconfigurations along the pipe (note: products in stock cannot be reconfigured).

The ability to reconfigure products creates two additional ways of fulfilling customers. Firstly, a proportion of customers will receive reconfigured products that then fully match their target specification. Secondly, a proportion of customers will receive reconfigured products that still do not match one or more of their non-critical features. Consequently, the results below include two additional graphs:

- proportion of customers fulfilled by reconfigured products that match their target specification for all critical and non-critical features;
- proportion of customers fulfilled by reconfigured products but the specification does not match on the non-critical features.

9.4.1 Spreading reconfiguration flexibility

This section observes the impact on fulfilment metrics of gradually increasing reconfiguration flexibility across all product features.

The simulation environment allows the reconfiguration flexibility for each feature to be set independently. For example, in condition S1 (of Table 9:4) only feature A can be reconfigured, and by

1 upward step only. In condition S8 all four features can be reconfigured by 1 or 2 upward steps. There is no restriction on the extent a product can be reconfigured, and so in condition S8 the producer can reconfigure a product by up to 8 option steps.

In condition 1 the flexibility is assigned to feature A. Given the customer population is behaving with random criticality, and that all features are equally likely to be fed into the pipeline and demanded by customers, the results would be the same if the flexibility were assigned to any one of the other three features. Consequently there is no need to repeat this condition with the flexibility shifted to another feature.

Flexibility can be increased up to 16 steps, with 1/0/0/0 being the first up to 4/4/4/4. Ten flexibility conditions are analysed, starting with zero flexibility and adding one unit of flexibility at a time, up to condition S8 in which all features have +2 flexibility. Condition S16 is the maximum flexibility situation, and a product entering the pipeline with a specification A1-B1-C1-D1 can be reconfigured into A5-B5-C5-D5.

Table 9:4 ***Spread*** **flexibility conditions**

Spread Condition	Flexibility of each product feature			
	Feature A	Feature B	Feature C	Feature D
0	-	-	-	-
S1	+1	-	-	-
S2	+1	+1	-	-
S3	+1	+1	+1	-
S4	+1	+1	+1	+1
S5	+2	+1	+1	+1
S6	+2	+2	+1	+1
S7	+2	+2	+2	+1
S8	+2	+2	+2	+2
S16	+4	+4	+4	+4

9.4.1.1 *Observations*

The majority of the impact of reconfiguration flexibility is accrued after 4 steps of flexibility (i.e. by condition S4). This is apparent from the graphs for the fulfilment mechanisms (Figure 9:33 to Figure 9:36). Pipe fulfilment becomes the dominant mechanism, with 50%-60% of customers fulfilled by this mechanism (Figure 9:35).

Further increases in flexibility do continue to alter the behaviour of the system. This is apparent from the plots of substituted and reconfigured customers in Figure 9:37 and Figure 9:38.

Introducing flexibility has little bearing on stock holding (Figure 9:40).

A notable impact of flexibility is that it reduces the differences in how the customer types are fulfilled. Across the fulfilment mechanisms the differences between the four customer types shrink, and a similar pattern is seen in average waiting times (Figure 9:42).

Figure 9:33 Proportions of customers fulfilled by mechanism in 10 flexibility conditions (Scenario 8)

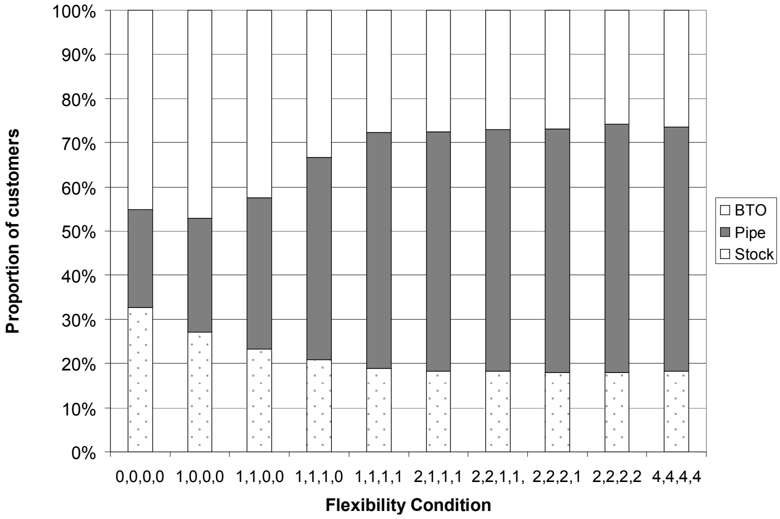


Figure 9:34 BTO fulfilment proportions for each customer type in 10 flexibility conditions (Scenario 8)

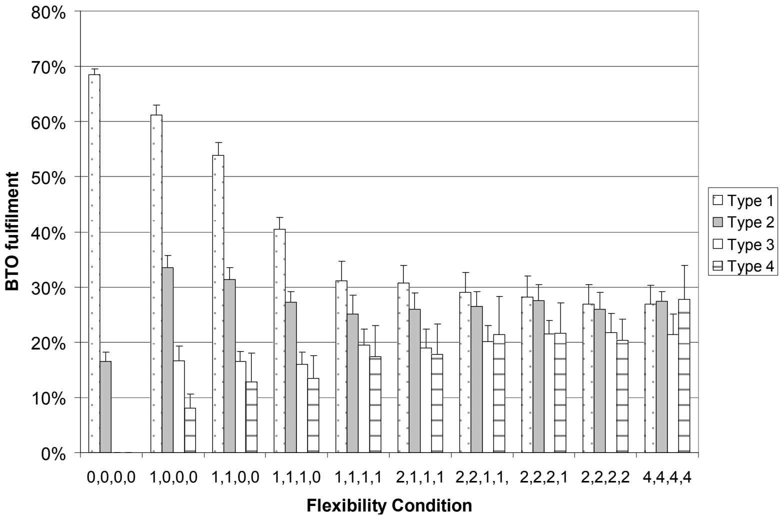


Figure 9:35 Pipe fulfilment proportions for each customer type in 10 flexibility conditions (Scenario 8)

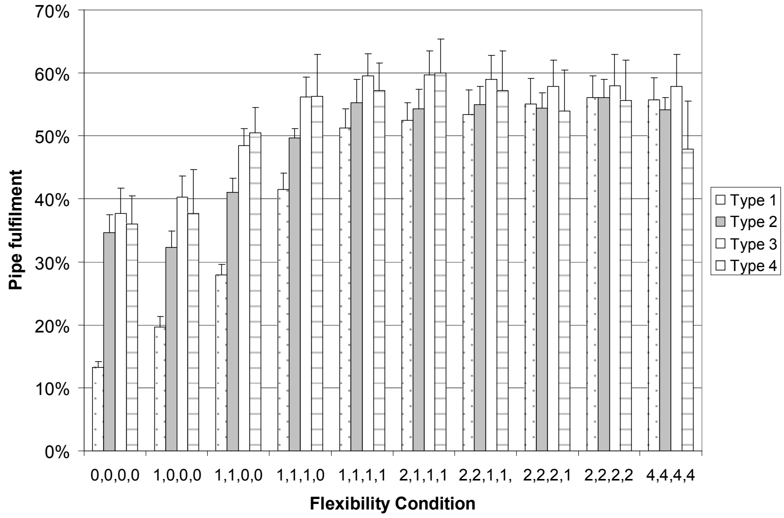


Figure 9:36 Stock fulfilment proportions for each customer type in 10 flexibility conditions (Scenario 8)

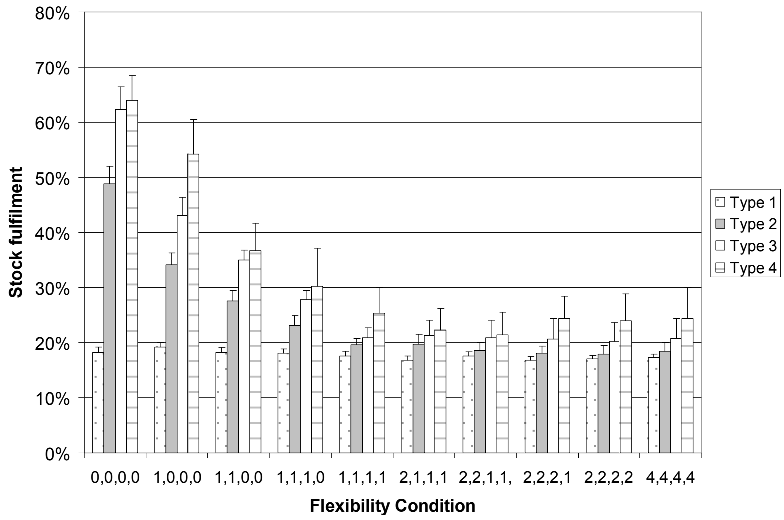


Figure 9:37 Substituting customers for each type in 10 flexibility conditions (Scenario 8)

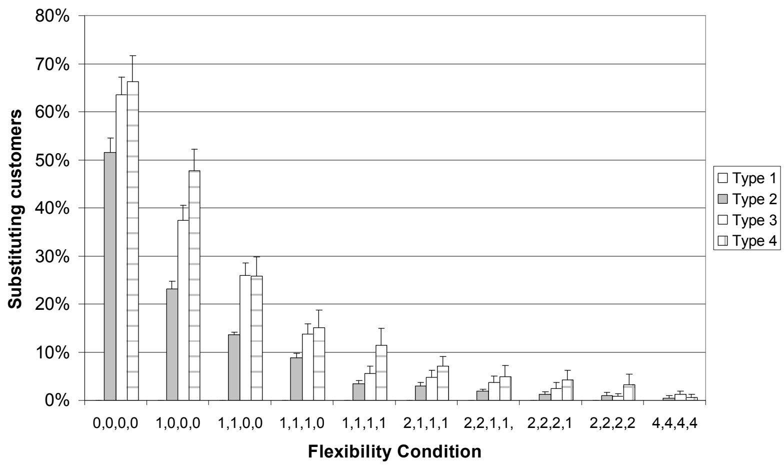


Figure 9:38 Reconfigured customers for each type in 10 flexibility conditions (Scenario 8)

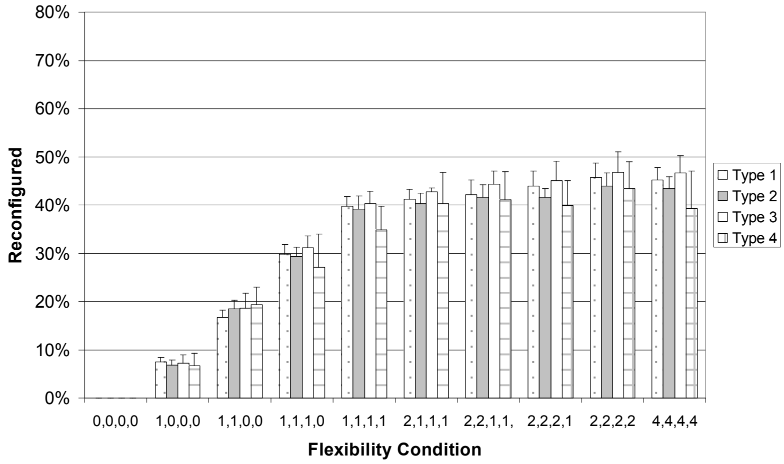


Figure 9:39 Reconfigured and substituting customers for each type in 10 flexibility conditions (Scenario 8)

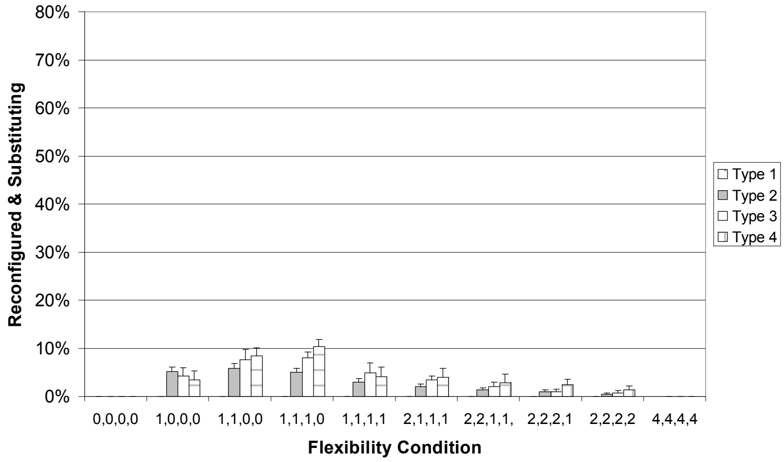


Figure 9:40 Stock holding in 10 flexibility conditions (Scenario 8)

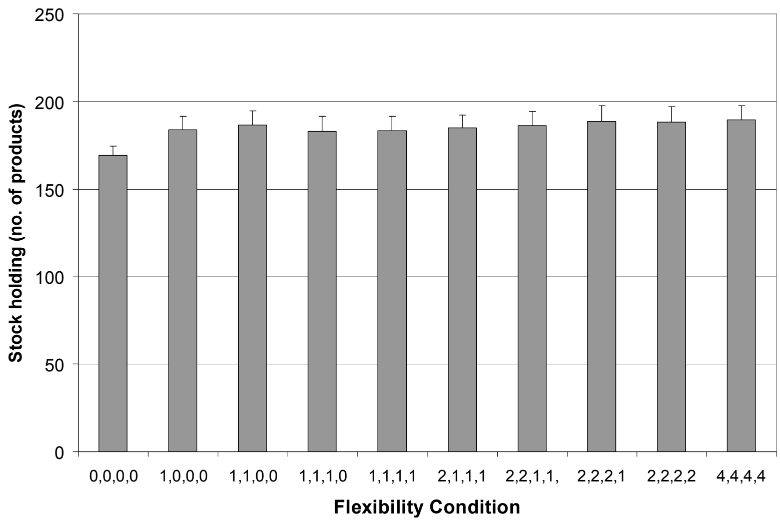


Figure 9:41 Average waiting time for all customers in 10 flexibility conditions (Scenario 8)

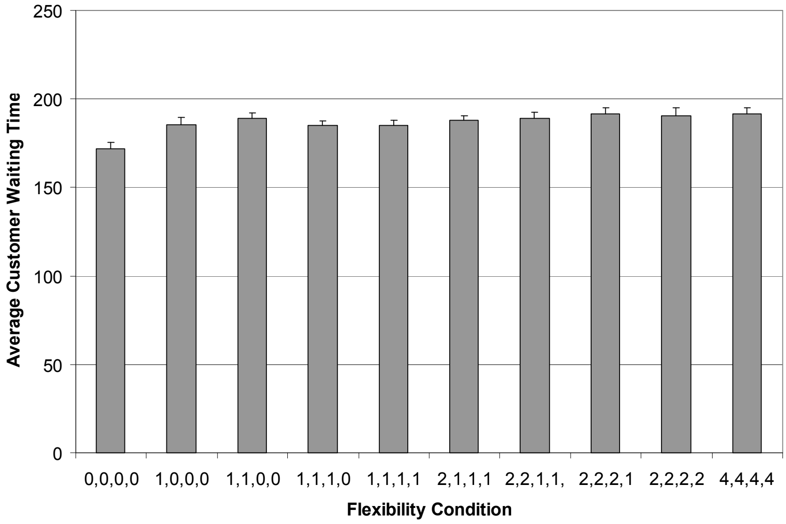
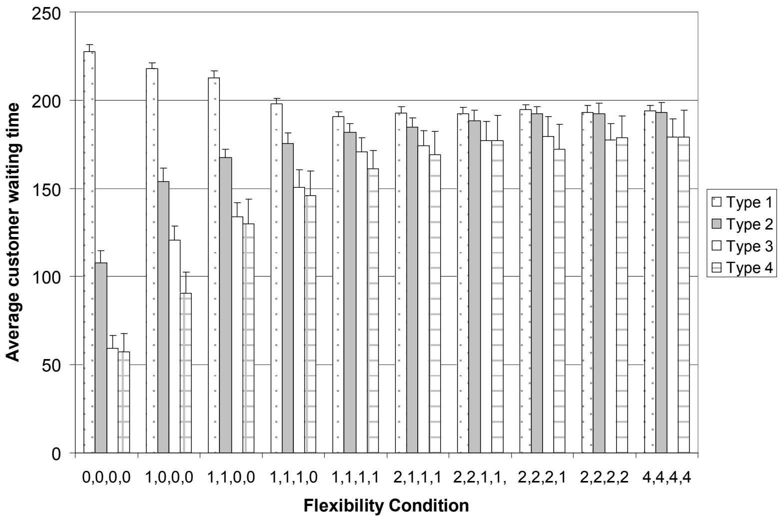


Figure 9:42 Average waiting time for each customer type in 10 flexibility conditions (Scenario 8)



9.4.2 Adjusting the pipeline feed with reconfiguration

With the ability to reconfigure products upwards (i.e. one-way reconfiguration) could the producer affect fulfilment performance by adjusting the balance of the feed into the pipeline? Specifically, should the producer bias the feed toward the lower options knowing that these can be reconfigured into the higher options? For example, when options can be reconfigured by one step upwards, any product entering the pipeline with an option 4 can satisfy exactly a customer wanting an option 5 as well one wanting an option 4. However, a product that enters with an option 5 can satisfy exactly only a customer seeking an option 5.

To investigate this question the balance in the feed is altered in 9 steps (Table 9:5). In the final step (RF9) no product entering the pipeline has option 5 for any of its 4 features. The flexibility condition S4 in Table 9:4 is studied (i.e. one-way upward flexibility (1/1/1/1) for customer mix scenario 8 (Table 9:1).

Table 9:5 Rebalanced feed conditions

Condition	Proportion of each option (applied to all 4 features)				
	Opt.1	Opt.2	Opt.3	Opt.4	Opt.5
RF0	0.2	0.2	0.2	0.2	0.2
RF1	0.205	0.205	0.205	0.205	0.18
RF2	0.21	0.21	0.21	0.21	0.16
RF3	0.215	0.215	0.215	0.215	0.14
RF4	0.22	0.22	0.22	0.22	0.12
RF5	0.225	0.225	0.225	0.225	0.10
RF6	0.23	0.23	0.23	0.23	0.08
RF7	0.235	0.235	0.235	0.235	0.06
RF8	0.24	0.24	0.24	0.24	0.04
RF9	0.25	0.25	0.25	0.25	0.0

9.4.2.1 *Observations*

The results reveal a producer can alter fulfilment by adjusting the feed. The pattern of fulfilment and customer waiting time is affected, with condition RF3 giving the lowest waiting time (Figure 9:50 and Figure 9:51).

As the number of products with option 5 is reduced, BTO fulfilment at first reduces and then increases (Figure 9:43 and Figure 9:44). Pipe fulfilment rises at first, then declines slightly (Figure 9:45). Stock fulfilment also rises at first but then declines (Figure 9:46).

Study of the three fulfilment mechanisms (Figure 9:44, Figure 9:45 and Figure 9:46) shows that differences between the four customer types become more pronounced the more the feed is altered.

The proportion of customers fulfilled by substitution remains constant for all feed conditions (Figure 9:47), but the proportion of customers fulfilled by reconfigurations rises to a peak and then declines (Figure 9:48). Taking these two graphs with Figure 9:49, which plots the proportion of customers fulfilled by a product that is reconfigured but is still not an exact match to their target specification, shows that the total proportion of reconfigurations and substitutions rises as the feed is adjusted.

Figure 9:43 Proportions of customers fulfilled by the three mechanisms in 10 feed conditions (Scenario 8, spread flexibility condition 1/1/1/1)

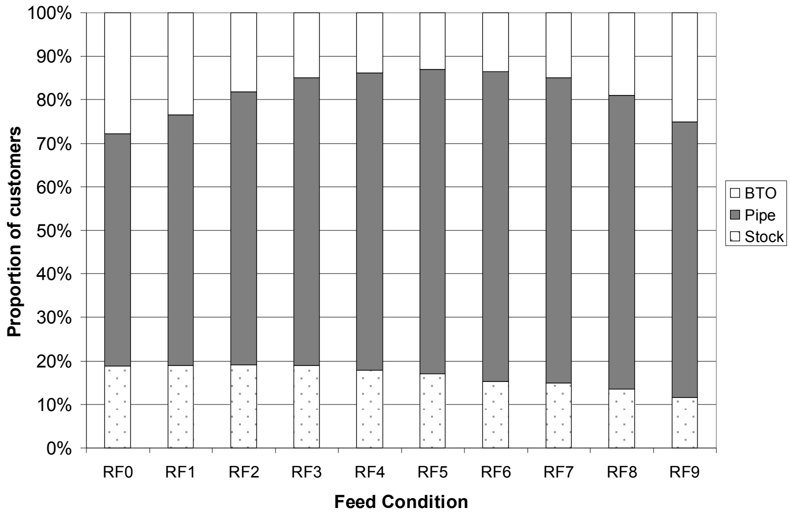


Figure 9:44 BTO fulfilment proportions for each customer type in 10 feed conditions (Scenario 8, spread flexibility condition 1/1/1/1)

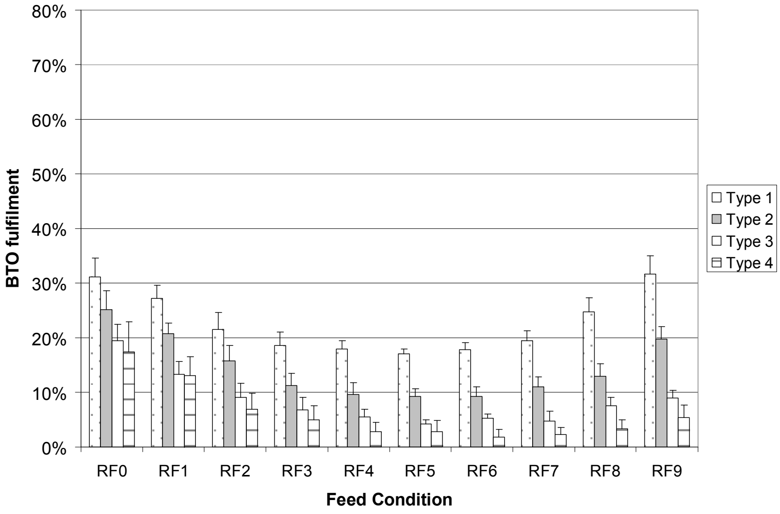


Figure 9:45 Pipe fulfilment proportions for each customer type in 10 feed conditions (Scenario 8, spread flexibility condition 1/1/1/1)

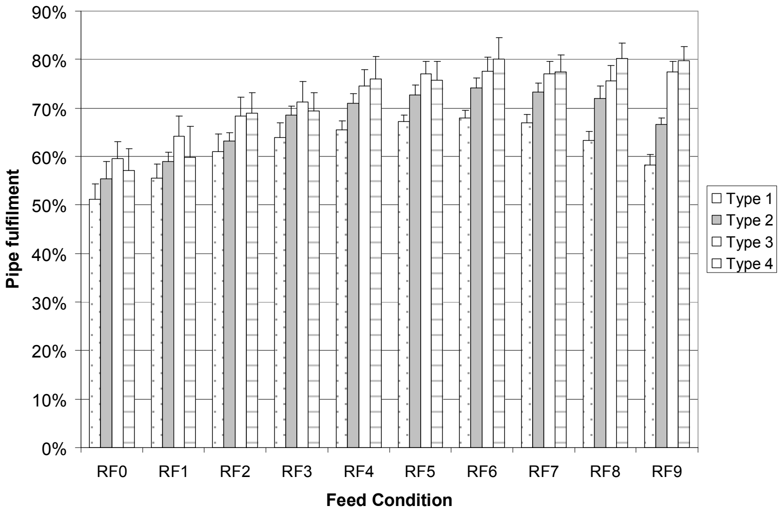


Figure 9:46 Stock fulfilment proportions for each customer type in 10 feed conditions (Scenario 8, spread flexibility condition 1/1/1/1)

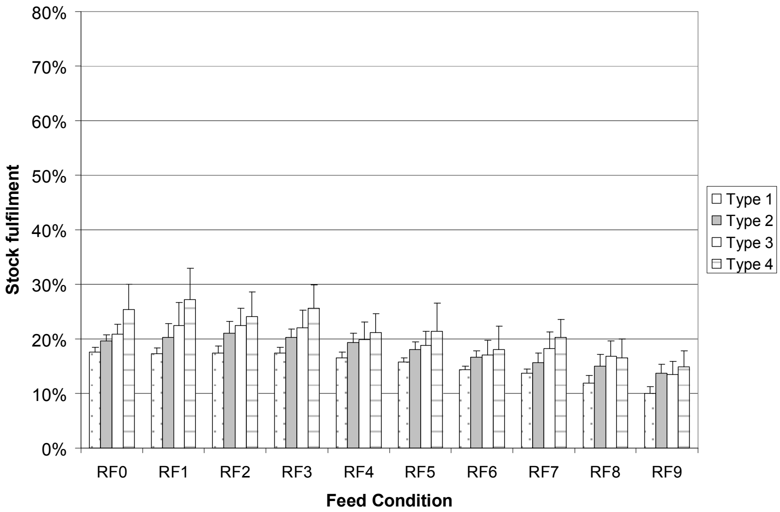


Figure 9:47 Substituting customers for each type in 10 feed conditions (Scenario 8, spread flexibility condition 1/1/1/1)

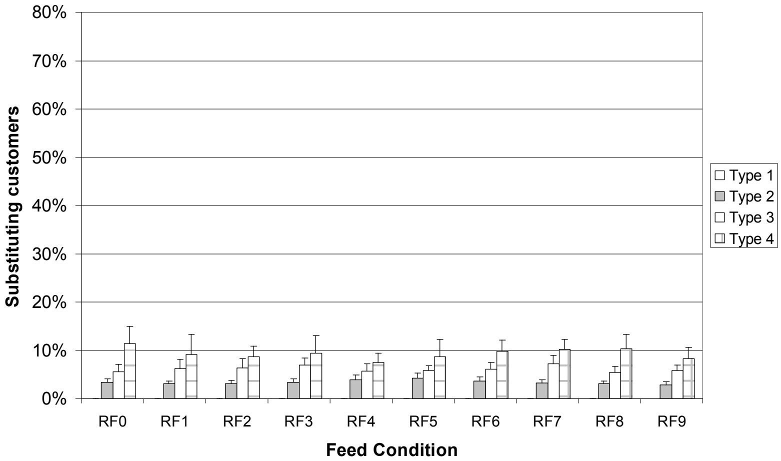


Figure 9:48 Reconfigured customers for each type in 10 feed conditions (Scenario 8, spread flexibility condition 1/1/1/1)

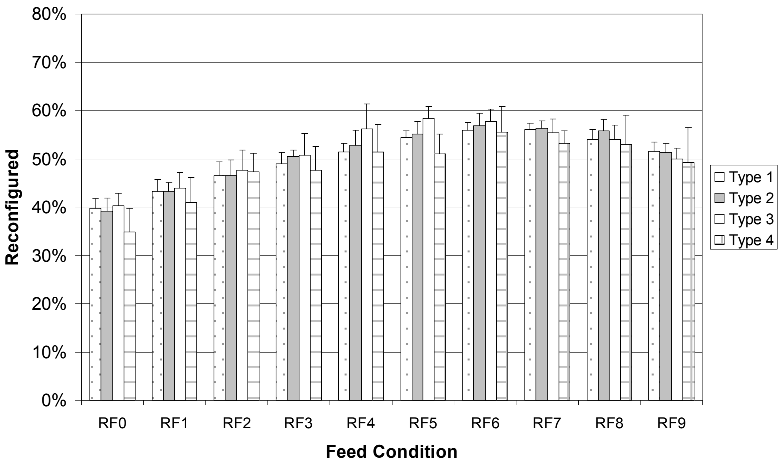


Figure 9:49 Reconfigured and substituting customers for each type in 10 feed conditions (Scenario 8, spread flexibility condition 1/1/1/1)

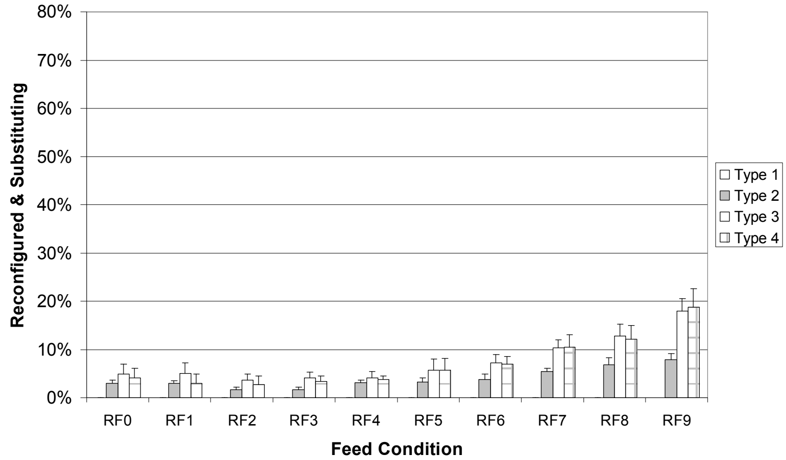


Figure 9:50 Average waiting time for all customers in 10 feed conditions (Scenario 8, spread flexibility condition 1/1/1/1)

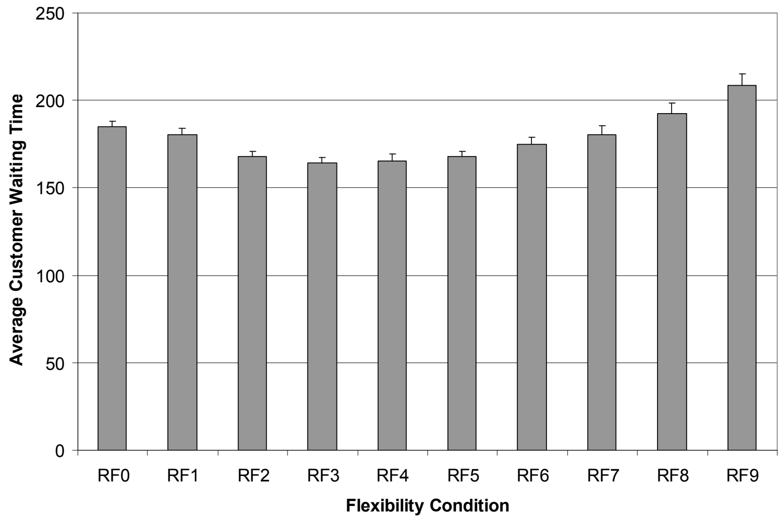
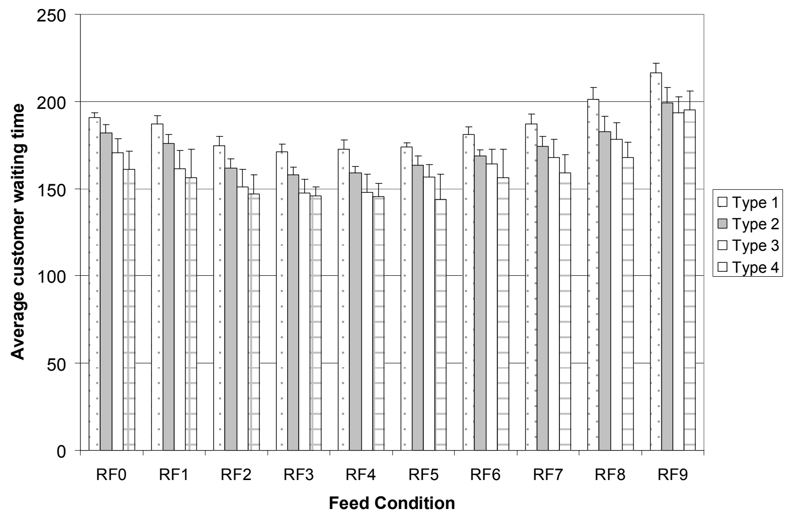


Figure 9:51 Average waiting time for each customer type in 10 feed conditions (Scenario 8, spread flexibility condition 1/1/1/1)



9.4.3 Alternative search policy – substitute first

The ability to reconfigure creates a further option for the producer. The producer can try to match every customer's target specification by reconfiguring products and fall back on substituting options as a second best, or the producer can give preference to fulfilling customers using substitutions and only reconfigure when necessary. The former is a *reconfiguration first* policy and the latter a *substitution first* policy. The results from sections 9.4.1 and 9.4.2 used the *reconfiguration first* policy and in this section the effect of the *substitution first* policy is investigated.

The effect of the two policies is studied as flexibility is increased in four steps (S1 to S4 in Table 9:4). The customer mix of scenario 8 is used (Table 9:1). In presenting the results the policies are denoted by 'r' and 's', i.e. r1/1/0/0 and s1/1/0/0.

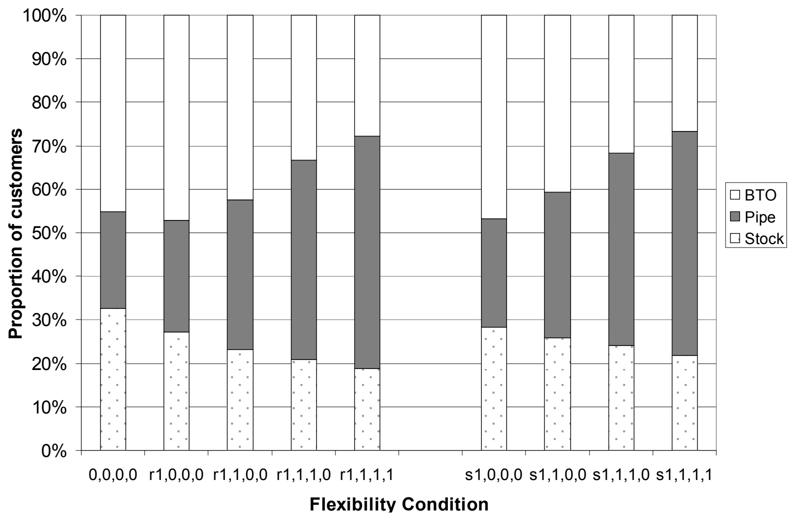
9.4.3.1 Observations[23]

The pattern of the fulfilment mechanisms shows similar behaviour (Figure 9:52) which is observed when looking at BTO fulfilment (Figure 9:53), but differences are present as observed in pipe and stock fulfilment (Figure 9:54 and Figure 9:55).

As would be expected, it is in the proportions of reconfigurations and substitutions where clear differences in the policies are observed. When the producer is using a *reconfiguration first* policy, as flexibility increases all customer types are handled in the same way with a growing proportion of them being fulfilled by reconfigurations (Figure 9:57) and fewer being fulfilled by substitutions (Figure 9:56). When the producer uses the *substitution first* policy, as flexibility increases there is less decline comparatively in the proportion of customers fulfilled by substitutions (Figure 9:56) and there are large differences in the proportions of each customer type receiving reconfigurations (Figure 9:57).

Waiting time homogenizes (Figure 9:60) and is a fraction lower in a substitution first policy (~5% 185 vs 177, Figure 9:59).

Figure 9:52 Proportions of customers fulfilled by the three mechanism (Scenario 8, four flexibility conditions, two search policies)



[23] The results from section 9.4.1 are being used for comparison

Figure 9:53 BTO fulfilment proportions for each customer type (Scenario 8, four flexibility conditions, two search policies)

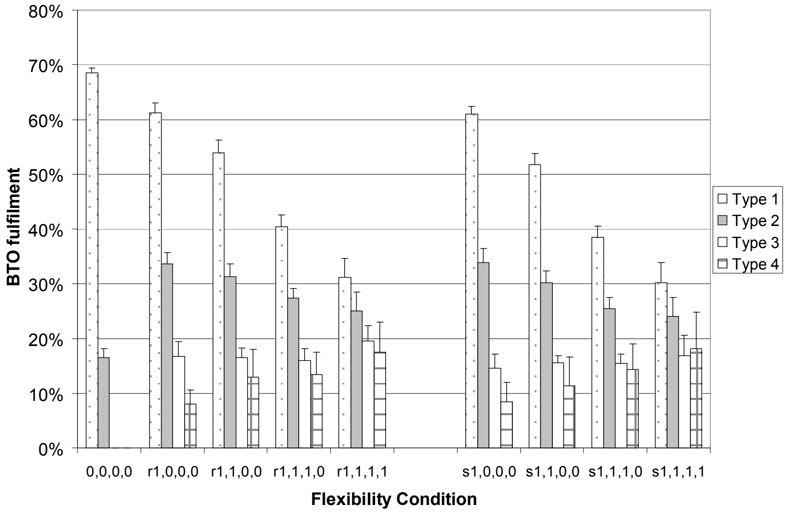


Figure 9:54 Pipe fulfilment proportions for each customer type (Scenario 8, four flexibility conditions, two search policies)

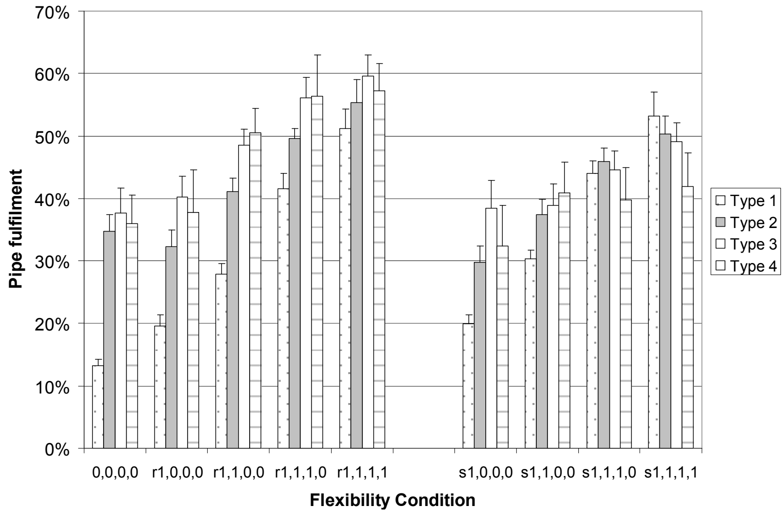


Figure 9:55 Stock fulfilment proportions for each customer type (Scenario 8, four flexibility conditions, two search policies)

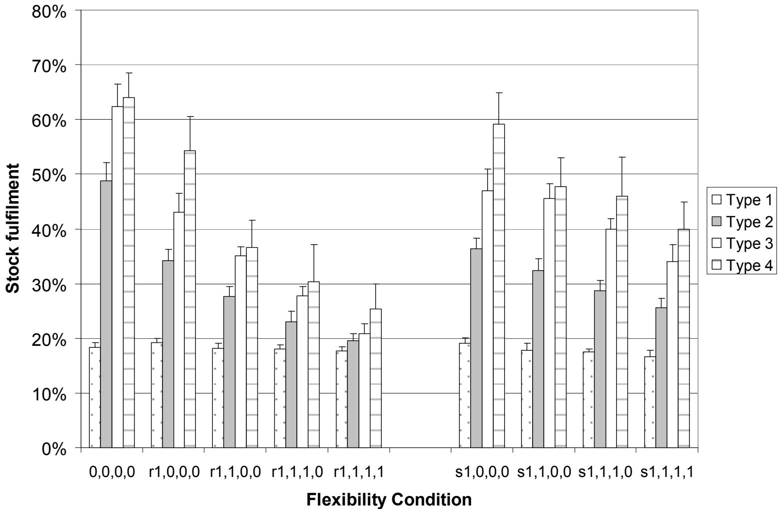


Figure 9:56 Substituting customers for each type (Scenario 8, four flexibility conditions, two search policies)

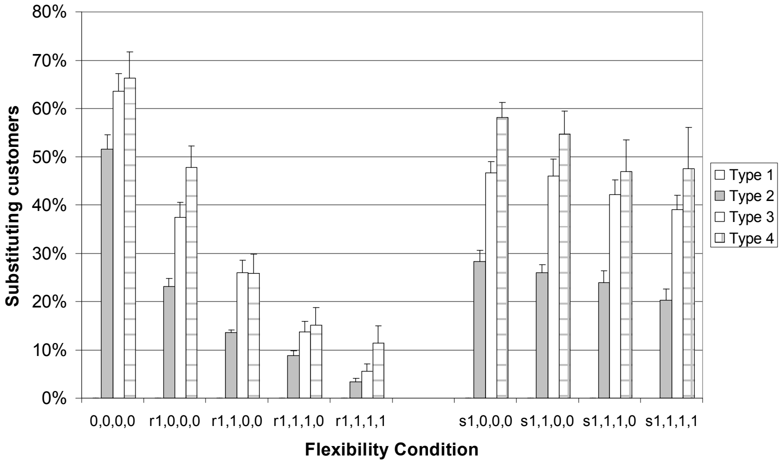


Figure 9:57 Reconfigured customers for each type (Scenario 8, four flexibility conditions, two search policies)

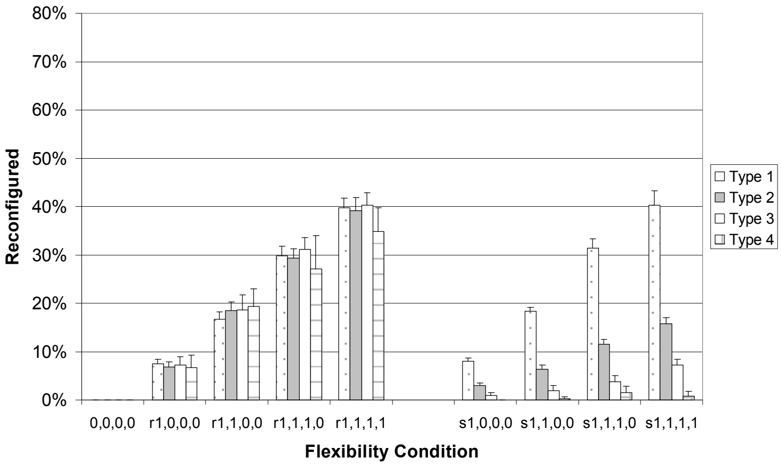


Figure 9:58 Reconfigured and substituting customers for each type (Scenario 8, four flexibility conditions, two search policies)

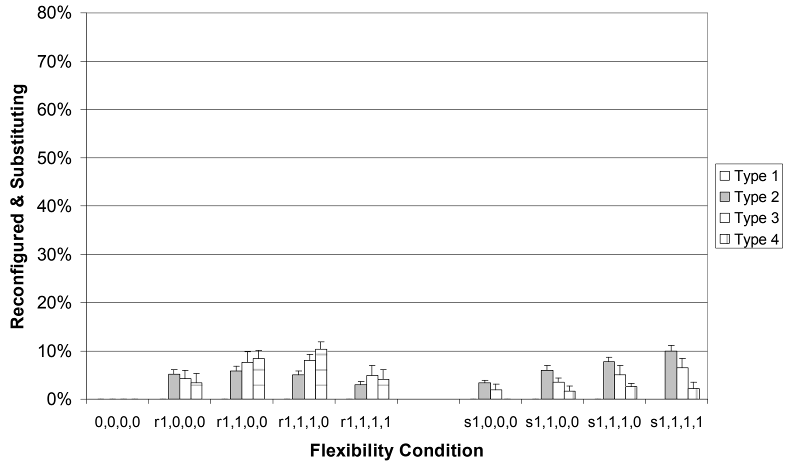


Figure 9:59 Average waiting time for all customers (Scenario 8, four flexibility conditions, two search policies)

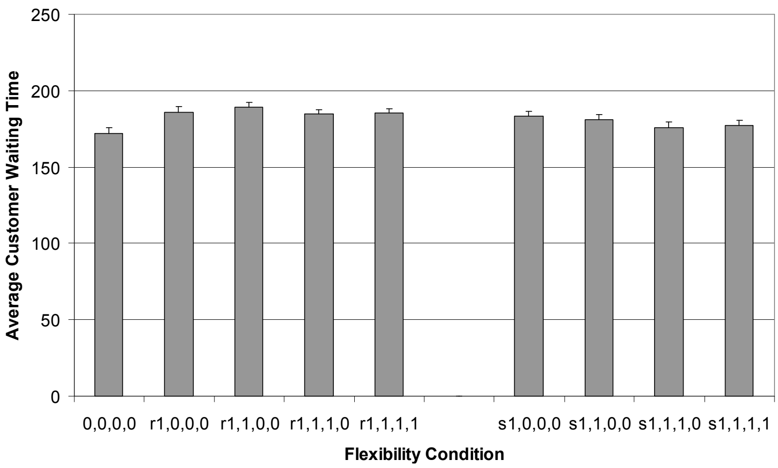
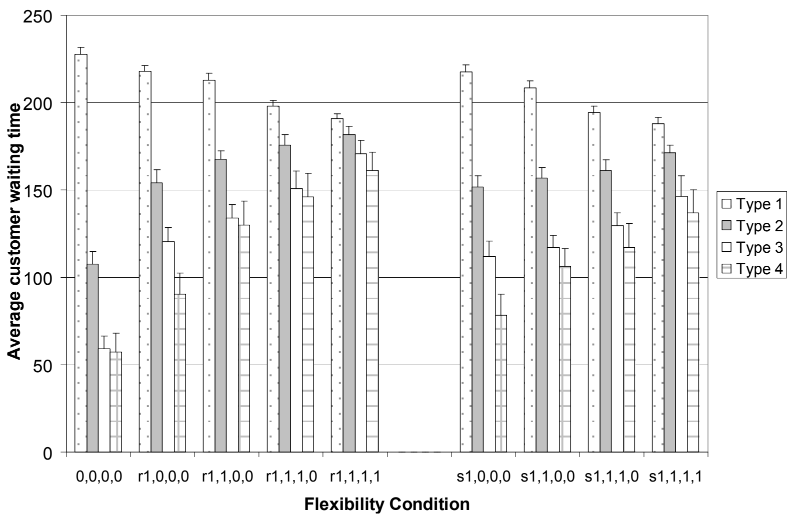


Figure 9:60 Average waiting time for each customer type (Scenario 8, four flexibility conditions, two search policies)



9.4.4 Focusing reconfiguration flexibility

This section observes the impact on fulfilment metrics of focusing flexibility in one product feature and compares it to spread flexibility studied in section 9.4.1 (page 125). Four conditions are analysed (Table 9:6), but only three are new as condition C1 is identical to condition S1 from earlier (Table 9:4).

Table 9:6 *Focused* flexibility conditions

Focused Condition	Flexibility of each product feature			
	Feature A	Feature B	Feature C	Feature D
C1	+1	-	-	-
C2	+2	-	-	-
C3	+3	-	-	-
C4	+4	-	-	-

9.4.4.1 Observations

In comparison to spreading flexibility across features, focusing flexibility has less impact on the behaviour of the VBTO system as illustrated in four graphs (Figure 9:61 to Figure 9:64). The trend is as observed for spread flexibility – a shift toward pipe fulfilment and the reduction in differences between customer types – but the extent of the shift is less. Giving maximum flexibility to one feature (condition C4, 4/0/0/0) has less effect than spreading the minimum flexibility across two features (condition S2, 1/1/0/0).

Figure 9:61 Proportions of customers fulfilled by mechanism in spread (left side) and focused (right side) flexibility conditions (Scenario 8)

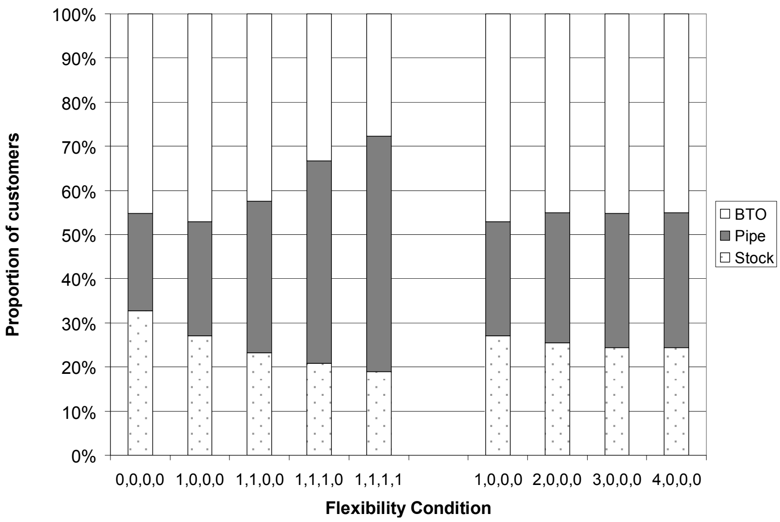


Figure 9:62 Pipe fulfilment proportions for each customer type in spread and focused flexibility conditions (Scenario 8)

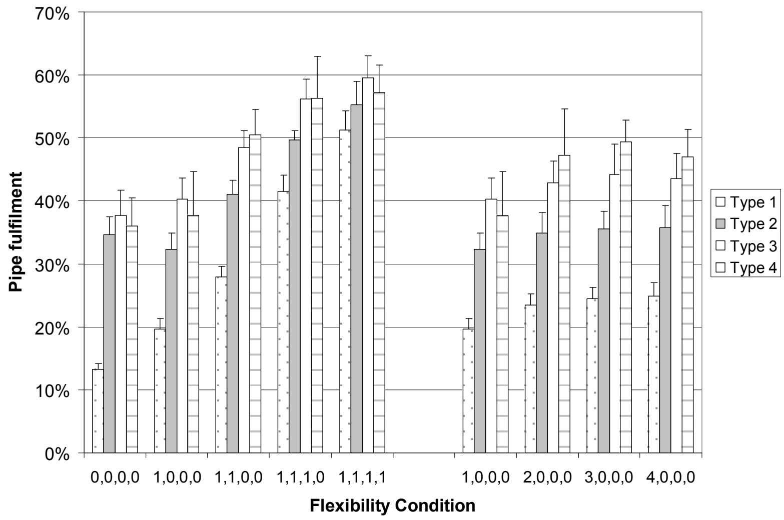


Figure 9:63 Reconfigured customers for each type in spread and focused flexibility conditions (Scenario 8)

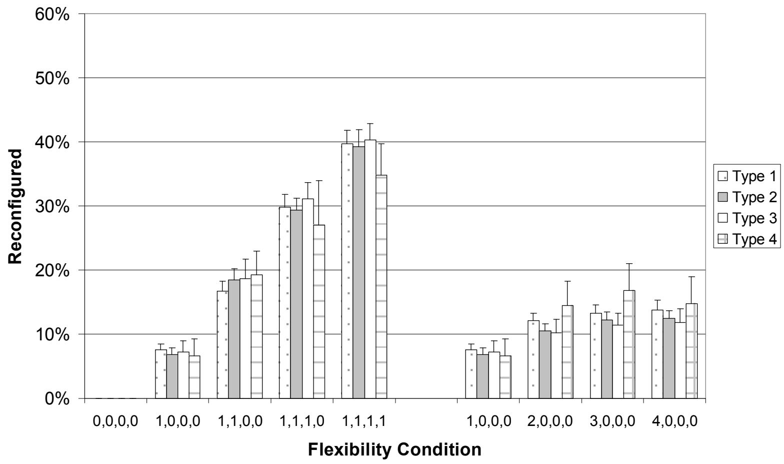
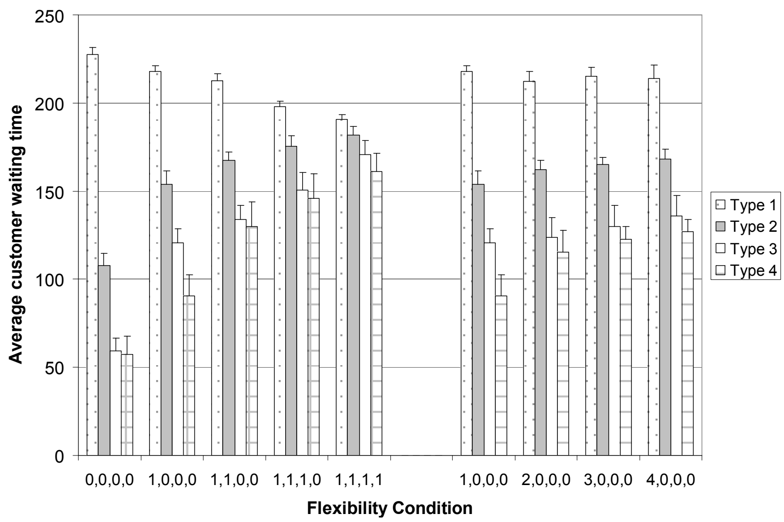


Figure 9:64 Average waiting times for each type in spread and focused flexibility conditions (Scenario 8)



9.4.5 *Two-way focused reconfiguration flexibility*

The comparison above showed that spreading one-way flexibility across the features has greater impact than focusing increased one-way flexibility onto one feature. Perhaps a more realistic comparison is with focused two-way flexibility, since if an enterprise is to invest in flexibility for a feature it would aim for two-way flexibility. In the figures below the results from repeating the scenarios in Table 9:6 are compared to the spread flexibility results, but this time with two-way focused reconfiguration flexibility.

9.4.5.1 *Observations*

As would be expected, two-way focused flexibility has a larger effect than one-way focused flexibility. In terms of the split between stock-pipe-BTO, full two-way focused flexibility (4/0/0/0) is equivalent to the 1/1/1/1 one-way spread flexibility condition (Figure 9:65). However, the two conditions are not equivalent in other ways. Firstly, focused flexibility does not remove differences in the fulfilment of customer types. Figure 9:66 compares the BTO proportions for each type in the spread and focused conditions and shows that in the spread condition 1/1/1/1 there is a 15% difference between customer types 1 and 4, whereas in the focused condition there is over a 30% difference. Comparisons of average customer waiting times in Figure 9:70 confirm the differences remain. Secondly, more customers receive substitutions and fewer receive reconfigurations with focused flexibility than with spread flexibility (Figure 9:67, Figure 9:68 and Figure 9:69).

Figure 9:65 Proportions of customers fulfilled by mechanism in one-way spread and two-way focused flexibility conditions (Scenario 8)

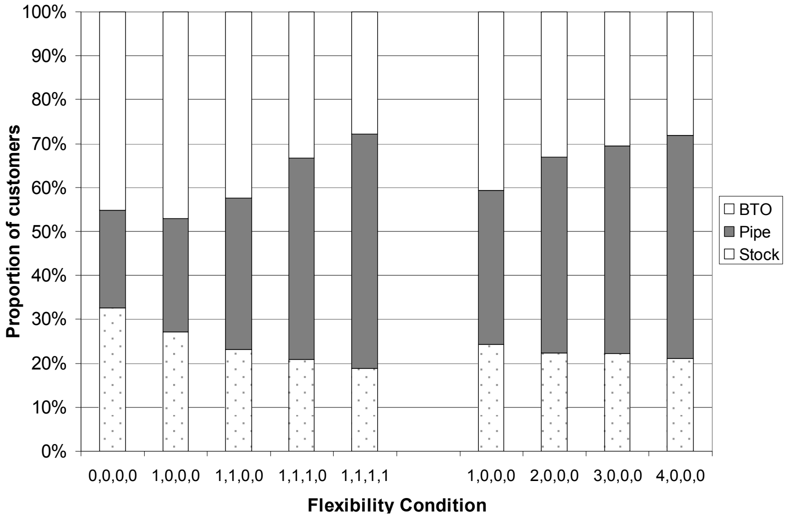


Figure 9:66 BTO fulfilment proportions for each customer type in one-way spread and two-way focused flexibility conditions (Scenario 8)

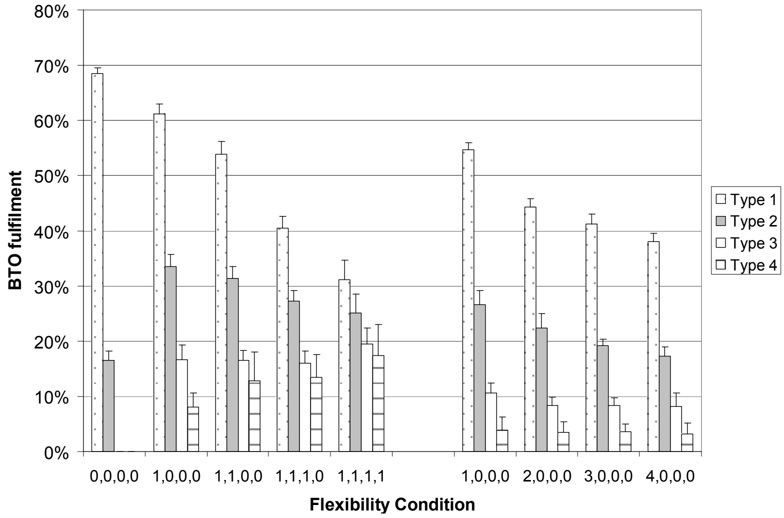


Figure 9:67 Substituting customers for each type in one-way spread and two-way focused flexibility conditions (Scenario 8)

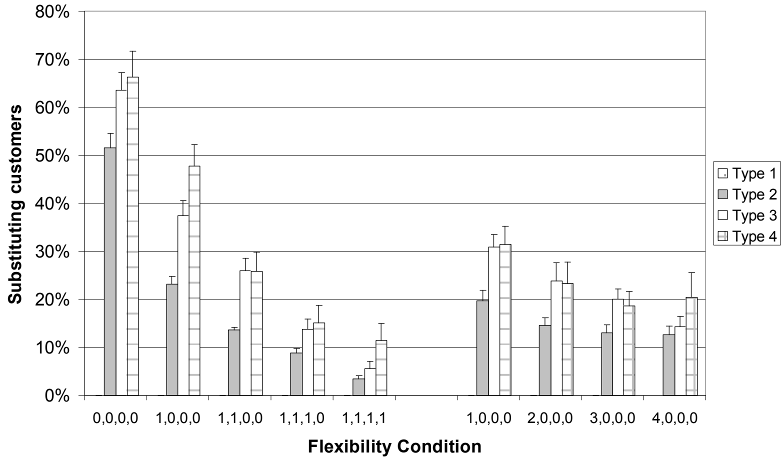


Figure 9:68 Reconfigured customers for each type in one-way spread and focused flexibility conditions (Scenario 8)

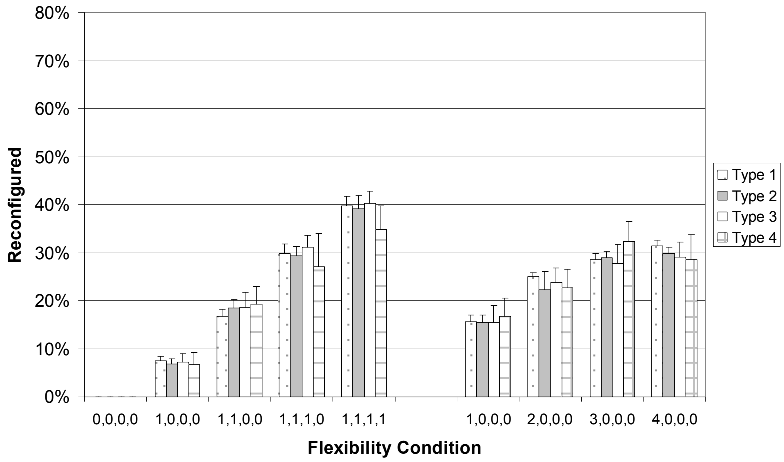


Figure 9:69 Reconfigured and substituting customers for each type in one-way spread and focused flexibility conditions (Scenario 8)

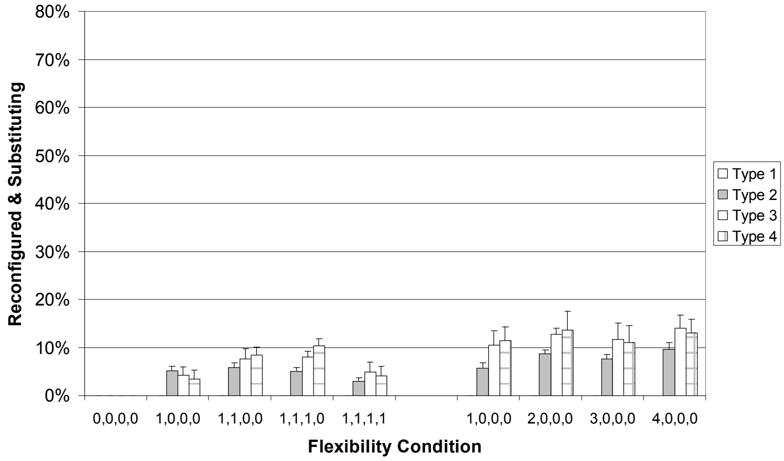
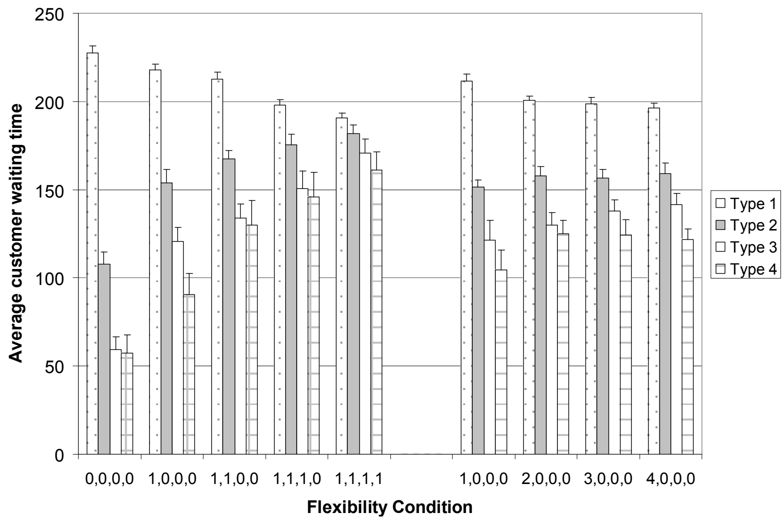


Figure 9:70 Average waiting times for each type in one-way spread and focused flexibility conditions (Scenario 8)



9.5 Common-criticality

Common-criticality models the circumstances in which customers have greater consensus about the product, and they rank the features in the same order. There is still a mix of views about how many product features are critical – i.e. some customers consider only one feature to be critical, others consider two to be critical and so on – but now all customers that have the same number of critical features identify the same features to be critical. The rules for criticality are set out in Table 9:7.

Table 9:7 Common-Criticality rules

Customer type	Criticality of product feature			
	Feature A	Feature B	Feature C	Feature D
1	✓	✓	✓	✓
2	✓	✓	✓	×
3	✓	✓	×	×
4	✓	×	×	×

9.5.1 *Common criticality without reconfiguration flexibility*

The first stage in the study of how common-criticality affects fulfilment behaviour is to test the conditions previously examined with no reconfiguration flexibility. The conditions from section 9.3.3 are applied:

- 9 customer mix scenarios as per Table 9.1 but with common feature criticality;
- Customers Types 2, 3 and 4 will accept substitutions (i.e. one-way upward compromise).

9.5.1.1 *Observations*

Comparing the results with those of section 9.3.3 (page 118) indicates there is a shift toward BTO fulfilment which indicates that common-criticality is more demanding (Figure 9:71). In line with the shift to BTO the average waiting time rises by up to 10% in the scenarios (Figure 9:72).

Figure 9:71 Relative differences in the proportions for each fulfilment mechanism from random to common criticality

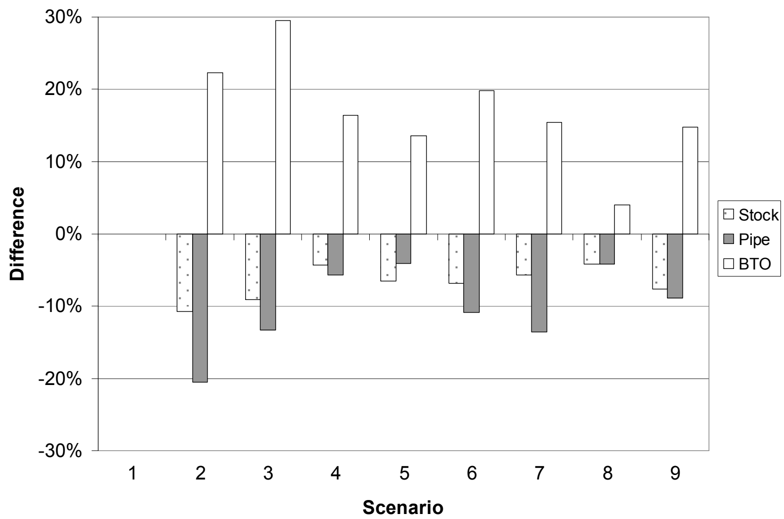
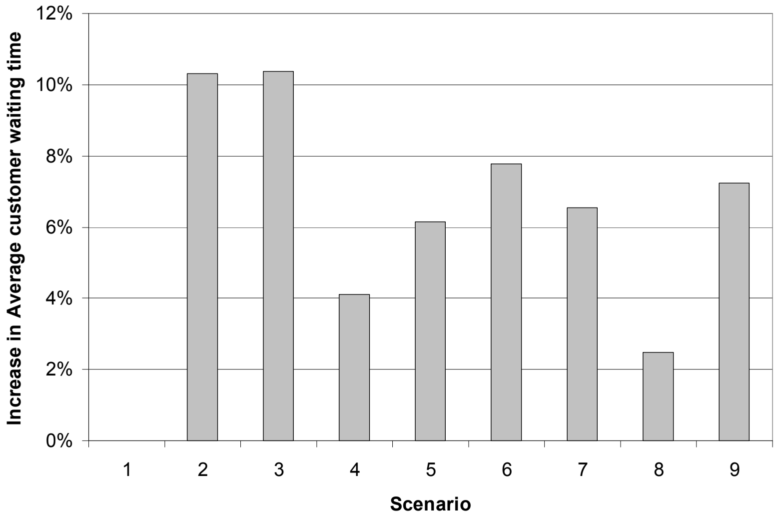


Figure 9:72 Relative difference in customer waiting time from random to common criticality



9.5.2 *Common criticality with reconfiguration flexibility*

In this stage of the study flexibility is introduced within the common-criticality environment. The flexibility conditions analysed are the same as in Table 9:4 and Table 9:6.

It should be noted that the sequence of introducing flexibility coincides with the critical features. Feature A is critical to all four customer types, and it is the first feature on which flexibility is introduced. Feature B is critical to three customer types and it is the next feature to have flexibility introduced, and so on.

9.5.2.1 *Observations*

The pattern of behaviour of the system as flexibility is increased is the same as was observed in the random-criticality conditions (section 9.4):

- there is shift in fulfilment to the pipe mechanism (Figure 9:73 & Figure 9:75 compared to Figure 9:33 & Figure 9:35 respectively);
- spreading flexibility across features has more impact than focusing on one feature (Figure 9:74 compared to Figure 9:61);
- the majority of the impact of reconfiguration flexibility is accrued after 4 steps of spread flexibility (i.e. by condition S4);
- increasing flexibility reduces differences in how customer types are fulfilled. Across the fulfilment mechanisms the differences between the four customer types shrink, and a similar pattern is seen in average waiting times (Figure 9:75 & Figure 9:76).

Figure 9:73 Proportions of customers fulfilled by each mechanism in 10 flexibility conditions (common criticality, Scenario 8)

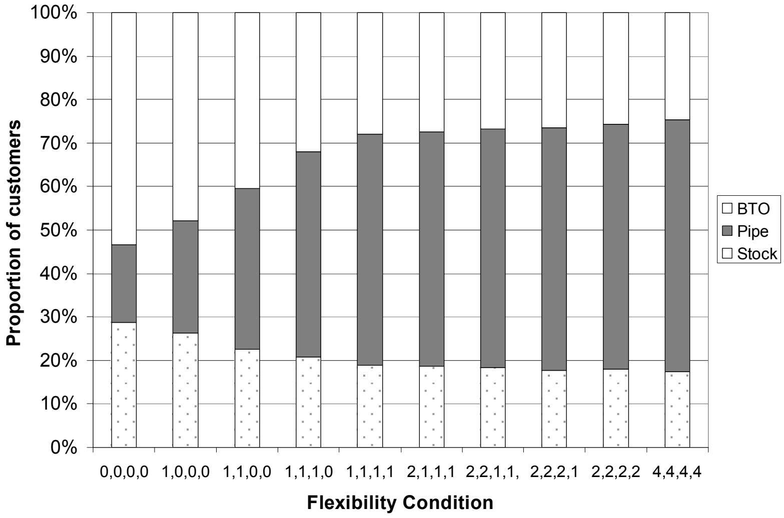


Figure 9:74 Proportions of customers fulfilled by each mechanism in 9 flexibility conditions (common criticality, Scenario 8)

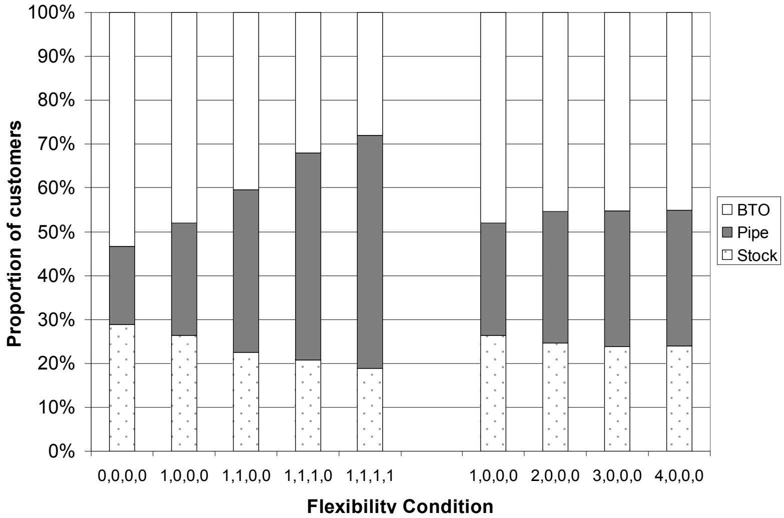


Figure 9:75 Pipe fulfilment proportions for each customer type in 10 flexibility conditions (common criticality, Scenario 8)

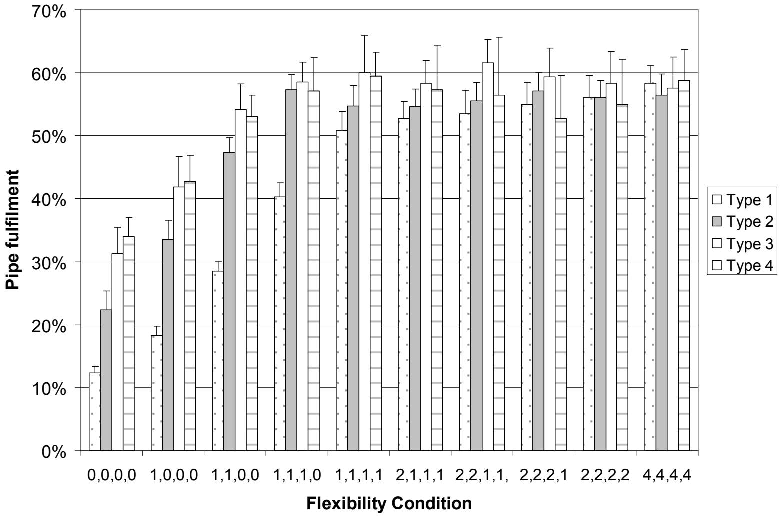
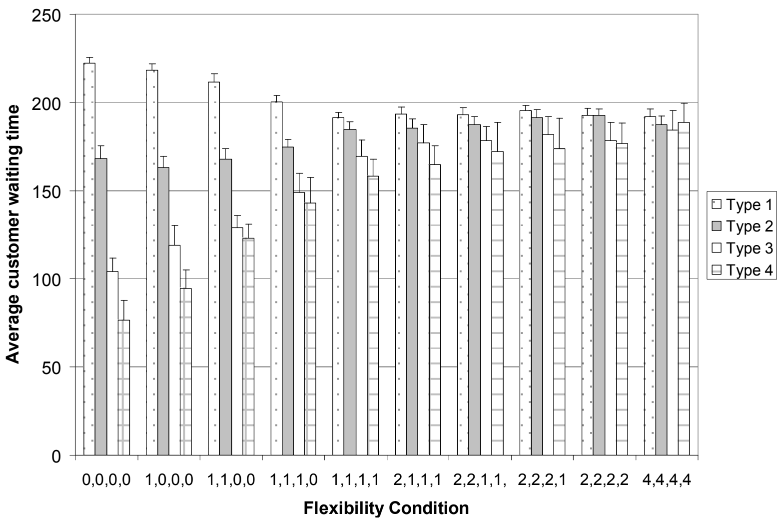


Figure 9:76 Average waiting time for each customer type in 10 flexibility conditions (common criticality, Scenario 8)



9.6 Discussion

The above studies have shown that when there are differences among customers in their acceptance of specification compromise, the customer mix has a significant impact on fulfilment metrics. Customers willing to compromise are flexible customers and the greater their proportion the greater the proportion of all customers fulfilled from the pipeline. When customers are flexible but accept substitutions (one-way compromise) on a feature the impact on fulfilment metrics is less than when they accept two-way compromise.

The producer has a number of options in configuring and operating the VBTO system – choice of search rule; balance of feed mix into the pipeline; spreading or focusing reconfiguration flexibility. The choices the producer makes have significant impact:

- In regard to search rule, using the *first suitable* rule takes advantage of the willingness of customers to compromise (or substitute) and shortens the delivery lead time (by 30% to 40% for compromising customers) at the expense of increasing the difference between the customer's target and delivered specification.

- By adjusting the feed mix, the producer can reduce the number of customers fulfilled by BTO and reduce waiting time by ~15% when the customer population has a majority of customers willing to accept substitutions but not any option on their non-critical features.
- In situations where there is balanced demand across the customizable features, a producer would be advised to spread flexibility across the features rather than focus flexibility on one feature. This is the case for common as well as random criticality environments.

As was observed in the previous chapter in sections 8.3.3 and 8.4.4, there is a diminishing benefit from reconfiguration flexibility. Once each feature has been given the lowest level of reconfiguration flexibility there is little benefit in adding more. A caveat to this observation is that the features had five options each. If they had, say, ten options, it may be that one step brings some benefit but that two or three steps bring the majority of benefit.

The more reconfiguration flexibility the producer has, the more that all customers are fulfilled in the same way in terms of waiting time, proportion receiving reconfigured products. Therefore flexibility homogenizes the customer population. For the most demanding customers (i.e. Type 1) the BTO route is required for fewer of them (e.g. when flexibility was spread across the features the proportion of Type 1 customers fulfilled by BTO halved, Figure 9:34). These customers also waited a shorter time (Figure 9:42). However, a downside of this homogeneity is that the waiting time for the most flexible customers is increased by a factor of 3.

This analysis suggests that to shorten waiting times for all customers the producer will need to shorten the pipeline. In Figure 9:77 and Figure 9:78 two shorter pipelines are compared to the pipeline of 300 that has been studied in this chapter. Figure 9:77 presents the fulfilment mechanisms, and the waiting times for each segment are plotted in Figure 9:78. The proportions fulfilled by BTO are higher for the shorter pipelines, as would be anticipated (see 9.3.1.1), but the reduced pipeline lengths shorten waiting times. The behaviour of the shorter pipelines is as expected when reconfiguration flexibility is added, with differences across customer types shrinking.

This chapter has not considered issues that could prevent the producer from shortening the pipeline, a key issue being the cost of reconfiguring products. In this chapter reconfigurations carry no cost or other penalty but in the next chapter a cost is added to the model.

Figure 9:77 Proportions of customers fulfilled by each mechanism in three pipeline lengths and 2 flexibility conditions (Scenario 8)

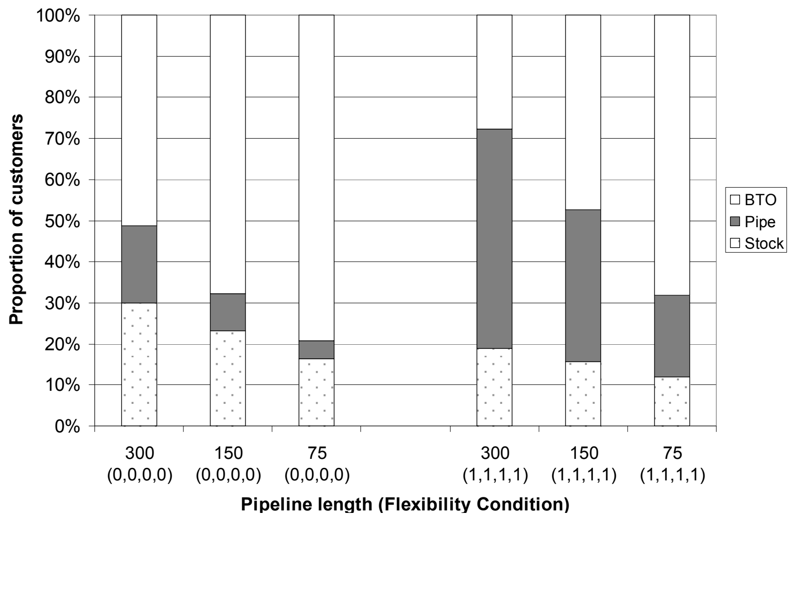
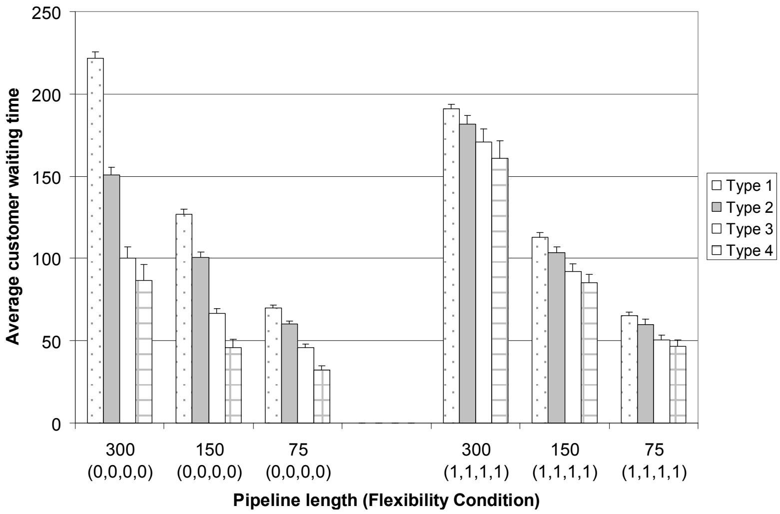


Figure 9:78 Average waiting time for each customer type in three pipeline lengths and 2 flexibility conditions (Scenario 8)



Chapter 10
Reconfiguration cost and customer aversion to waiting

Abstract

Fulfilment is modelled as a trade-off between cost of fulfilment and customer satisfaction. The customer population is divided into two segments that differ in their aversion to waiting. The product is modelled as having four customizable features and the cost of reconfiguring these features depends on the position of the product along the pipeline. The analysis shows how fulfilment performance is dependent on the customer mix and shows that the more willing the producer is to accept the additional cost of reconfiguration the more the producer is able to differentiate between the customer segments.

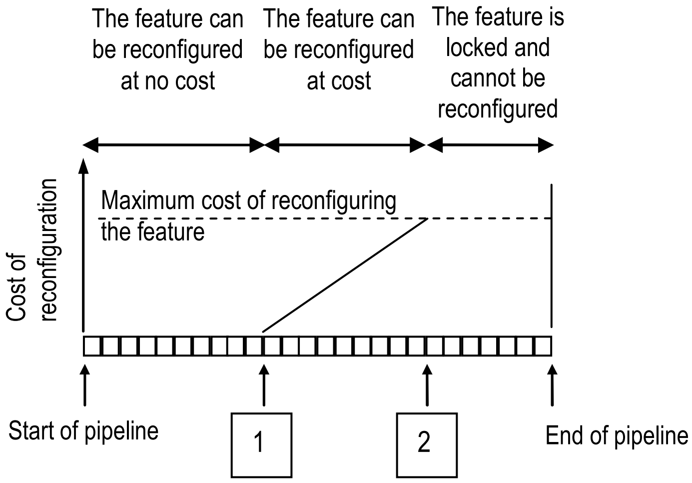
10.1 Introduction

This chapter looks at two factors – cost of reconfiguration and customer aversion to waiting. The previous two chapters studied how reconfiguration flexibility altered fulfilment performance, in particular, how fulfilment was affected when placing restrictions on the extent to which a product can be reconfigured. In this chapter a different perspective of reconfiguration is taken. Here the producer can reconfigure a product fully but the cost of reconfiguring it increases as the product progresses along the pipeline. The later the producer waits to reconfigure, the more it will cost.

The cost of reconfiguration is modelled as an additional cost which is also the approach used by Balakrishnan & Geunes (2000) to model their conversion costs. If a product is reconfigured at the very last point in the pipeline, the cost of the product is doubled. If no product in the pipeline is amended, there will be zero additional cost. To simplify the analysis the cost of all variants is assumed to be equal, and the additional cost of reconfiguration is the same regardless of which variant the product is reconfigured from and to. This approach is consistent with a view that reconfiguration cost is a function of the fulfilment (and supply chain) processes rather than of the product.

As in the previous chapter, the product is modelled as having a modular architecture with four features, and a number of options per feature. Each feature is given its own reconfiguration cost curve of the form illustrated in Figure 10:1. When the product has entered the pipeline but has not reached point 1 the feature can be reconfigured without cost. Between points 1 and 2 the feature incurs an increasing reconfiguration cost. After point 2 the feature cannot be reconfigured. In this study the four features each have a unique point 1, but all share the same point 2.

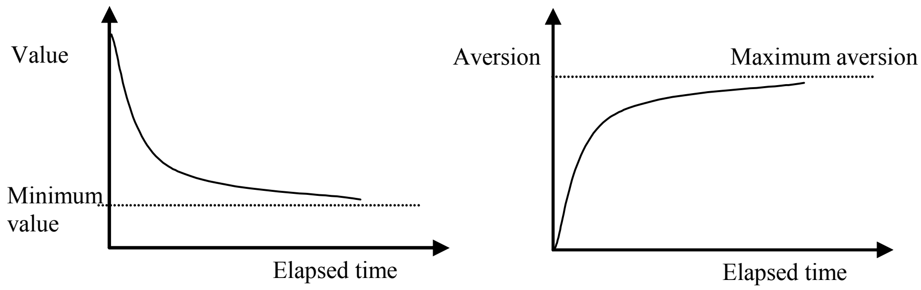
Figure 10:1 Schematic of reconfiguration cost curves for the four features



Putting a cost on reconfiguration can be expected to alter the attitude of the producer to using it to fulfil customers. Unless there is good reason to incur the cost, the producer will avoid it. The second factor that is introduced – customer aversion to waiting - provides the counter weight.

The aversion a customer has to a delay in receiving their purchase is due to the decay in value over time (see section 6.2.3.5). Customers perceive value to decline as time elapses (Figure 10:2 left graph) which can be transformed into an aversion to waiting (Figure 10:2 right graph). An increasing aversion factor represents the customer's increasing aversion to the length of their wait. Therefore, the attractiveness of a product to a customer is influenced by the position of the product in the pipeline. 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 latter product.

Figure 10:2 Correspondence between value decay and aversion to waiting



In this study the customer population is divided into two segments, with one segment being more strongly averse to waiting than the other. To satisfy a customer the producer needs to take account of the customer's aversion to waiting and hence for the delay-averse segment the producer must avoid long lead times which will result in the producer incurring reconfiguration costs.

This chapter describes and studies a fulfilment procedure in which reconfiguration cost and customer delay aversion are used to control the allocation of products to customers. For all customers all of the product features are critical, hence they all must receive an exact match to their target specification.

10.2 Approach

10.2.1 Operationalizing reconfiguration cost

As introduced above, 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[24]. The algorithm for calculating reconfiguration cost is given in equation [10-1]. It generates a value equal to or 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. When reconfiguration incurs no additional cost it returns 1.

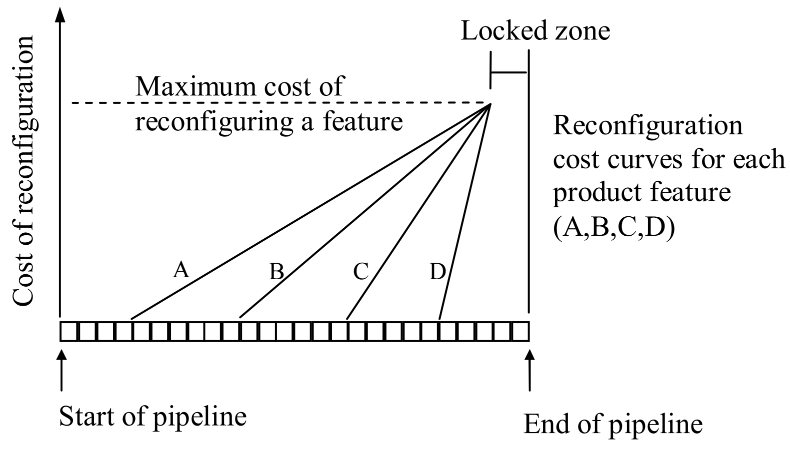
$$RCM_j = {}_{i=1}\Sigma^n (\delta c_{ij} \times fc_i) + 1 \qquad [10\text{-}1]$$

RCM_j is the **Reconfiguration Cost Multiplier** for a 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 *fractional cost increase* (δc) is defined by the feature's *reconfiguration cost curve*. In most of the experiments in this chapter each feature (A, B, C, D) has four options and an independent cost curve (a schematic of a cost curve is presented in Figure 10:3). 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 10:1. Note the pipeline length is 90 in all experiments in this chapter.

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 10:3 Schematic of reconfiguration cost curves for the four features



[24] As was the case in the earlier chapters, a product can be reconfigured when being allocated to a customer, hence it can be reconfigured only once.

Table 10:1 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

10.2.2 Operationalizing customer delay aversion

Aversion to waiting is modelled as an exponential function, with the *decay rate facto*r and *maximum decay* being control variables [10-2].

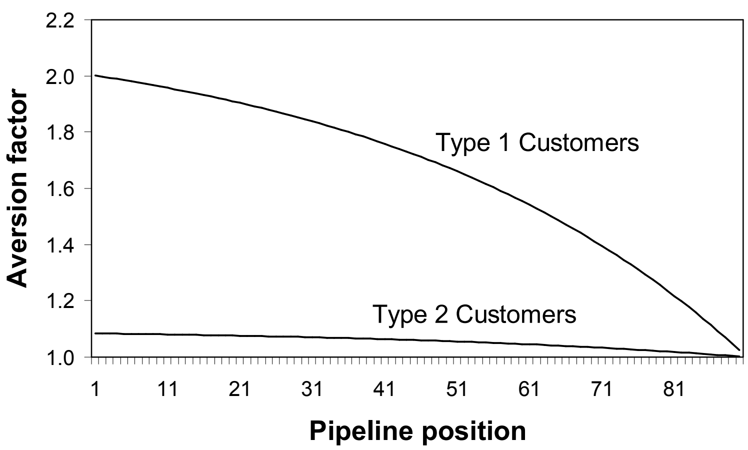
$$DA_{kj} = m_k - \mathrm{Exp}(df_k\,(L - j + 1)(m_k - 1)) \quad [10\text{-}2]$$

DA_{kj} is the **Delay Aversion Factor** of product in position j for customer type k
m_k is the maximum delay aversion for customer type k
df_k is the decay rate factor for the customer type k
L is the length of the pipeline
j is the position of product along the pipeline

A product about the leave the pipeline (i.e. when $p_q = L$) 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, but a different maximum delay aversion (m), which is set at 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 10:4.

Figure 10:4 Delay aversion factor (da) for Type 1 and Type 2 customers



10.2.3 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 upstream start of the pipeline.

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:

$Index_{kj} = RCM_j \times DA_{kj}$ [10-3]

$Index_{kj}$ is the search index value of the product in pipeline position j for the customer type k

If two or more products can have the same reconfiguration cost multiplier 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 and therefore be allocated to the customer in preference to 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[25].

10.2.4 System variables

In these studies a pipeline length of 90 units is used throughout. The product is modelled as having four features. In all sub-studies there are 4 options per feature, giving a total of 256 variants. In the first sub-study 2, 3, 5 and 6 options are also simulated (equating to 16, 81, 625 and 1296 variants).

The combination of 256 variants and a pipeline length of 90 gives a variety/ pipeline ratio of ~2.8, under which conditions a small but significant proportion (~10%) of customers would find an exact match in the pipeline if there were no reconfiguration flexibility using a backwards search and the majority would be fulfilled by the BTO mechanism (see Figure 8:17 on page 79). The selection of parameters therefore allows the influence of reconfiguration flexibility to be observed.

The production rate is fixed at one product per time period. Customer arrival rate is constant and equal to the production rate.

The sequence of products fed into the pipeline is random with all variants having equal probability. The sequence of specifications demanded by customers is also random and all variants have equal probability.

10.2.5 Performance Metrics

The following performance metrics are used:

- 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 cost of fulfilment for both customer types;
- proportion of both customer types fulfilled by reconfigured products.

10.2.6 Study stages

The study is divided into four stages. In the first stage, the two types of customer are in equal proportion and the system is studied with the condition that no reconfiguration cost is incurred, i.e. the producer is unwilling to incur any additional reconfiguration costs, so only costless reconfigurations are permitted. In the second stage the effect of increasing the producer's willingness to incur reconfiguration costs is investigated. In the third stage the mix of the two customer types is varied to explore whether fulfilment metrics are sensitive to mix. The last stage studies the effect of mismatches between the pipeline feed mix and the customer demanded mix.

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[25] In these experiments there is always at least one available product in the pipeline because customer inter-arrival time is constant and balanced with the production rate. Hence, between each customer arrival a new product enters the pipeline. In the studies in this chapter this product is <u>fully</u> reconfigurable and so can be reconfigured to match the customer's target specification.

10.3 Results

10.3.1 Costless reconfigurations only

Although the two types of customers have different aversions to waiting, when the producer is unwilling to incur additional costs both customer types have near identical fulfilment performance. As variety increases the waiting time increases for both customer types in harmony (Figure 10:5). The proportion of customers fulfilled by reconfigured products follows the same pattern and again there is no difference between the two customer types (Figure 10:6).

As product variety increases, the steady-state stock holding increases. In the simulation system there are always 90 unallocated products. This is because a) the customer arrival rate and production rate are equal, b) every customer is fulfilled, c) the system starts with the pipeline full and stock empty, and d) when a customer arrives, one product is allocated to them, and before the next customer arrives a new product enters the pipeline.

At the lowest variety level studied (i.e. a product structure of 2/2/2/2), customers are fulfilled as follows: 40% by reconfigurations in the pipeline, 30% from stock and 30% by exact matches in the pipeline (Figure 10:7). The average waiting time is just above 30% of the pipeline length (Figure 10:5).

At the highest variety level studied (i.e. product structure 6/6/6/6) the dominant mode of fulfilment is by reconfigurations in the pipeline (~95%) which take place at the upstream end of the pipeline (indicated by the average waiting time being ~80% of the pipeline length).

Figure 10:5 Waiting times of Type 1 and Type 2 customers

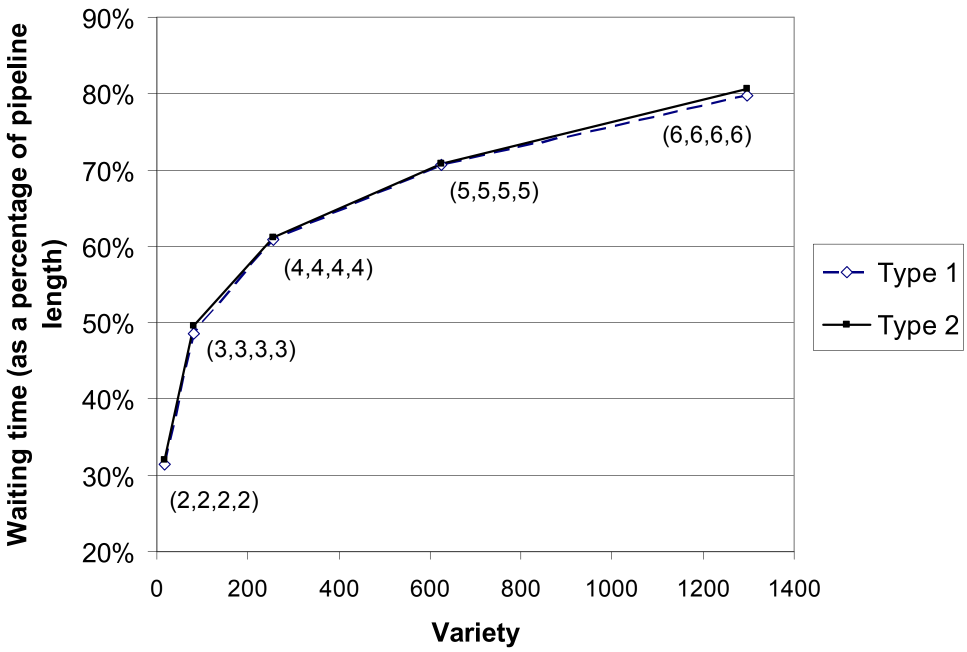


Figure 10:6 Proportion of Type 1 and Type 2 customers fulfilled by product reconfigurations

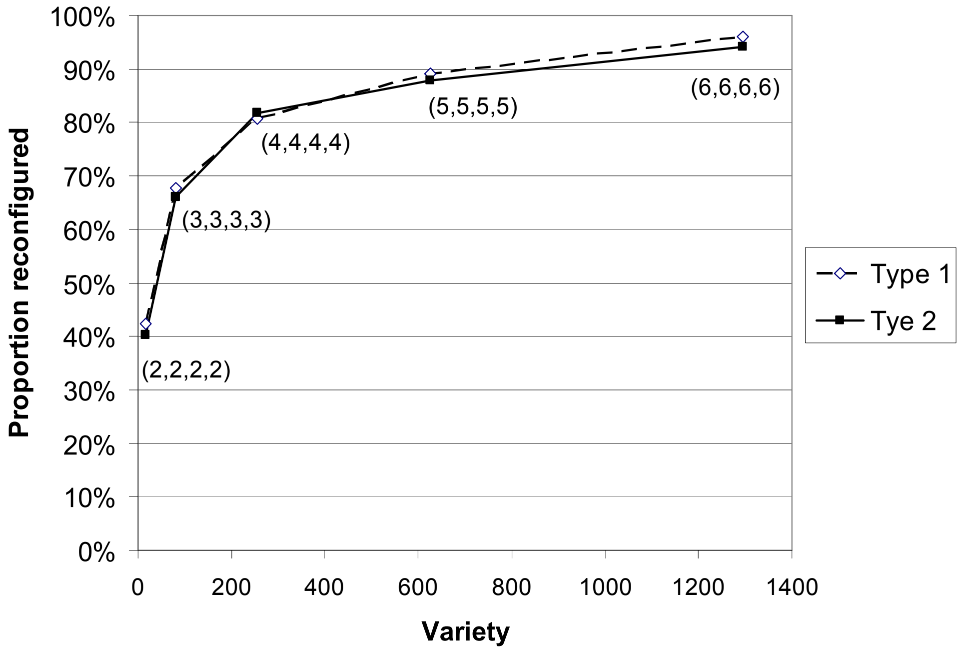
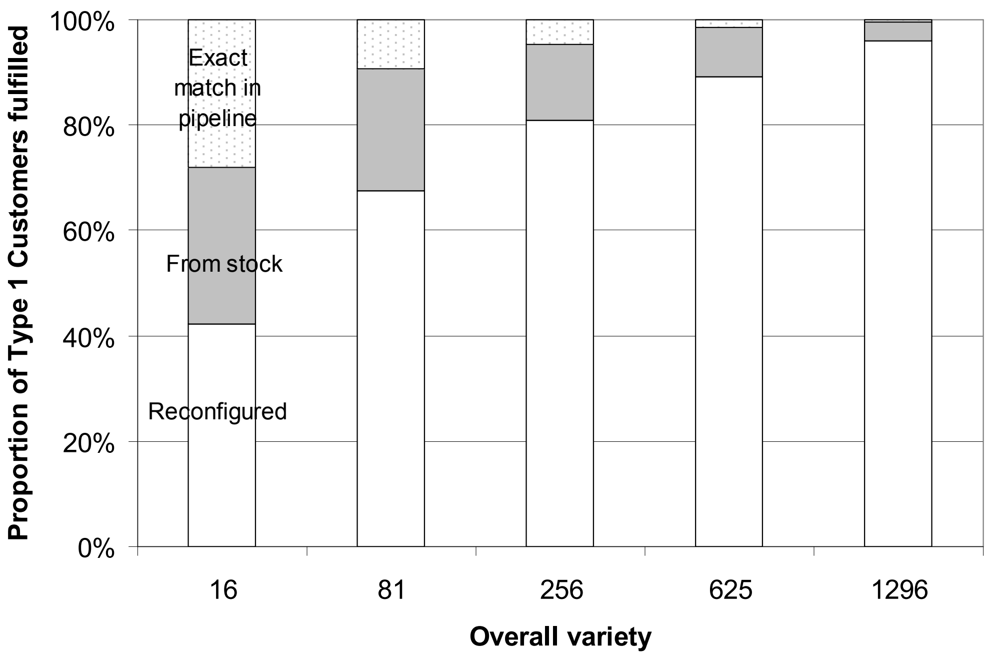


Figure 10:7 Fulfilment methods



10.3.2 Increasing the limit on reconfiguration cost

Gradually increasing 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 10:8 shows how the average fulfilment cost multiplier for Type 1 customers rises markedly as the limit on reconfiguration cost is raised (from 1.01 to 1.6). Raising the limit on cost does not alter the proportions of either customer type fulfilled by reconfigured products, which remain at just above 80%, but it shifts away from costless reconfigurations for Type 1 customers (Figure 10:9). The waiting time for both customer types decreases, with waiting time for Type 1 falling by 50% when comparing the cost limits of 1.01 and 1.5 and by 10% for Type 2 customers (Figure 10:10).

These results indicate that a limit of between 1.2 and 1.3 on the reconfiguration cost has little detriment to customers in terms of waiting time, but benefits the producer by reducing average fulfilment cost. If the maximum is set to 1.3, the reduction in average additional cost per Type 1 customer is 15% (from 1.066 for a limit of 1.6 to 1.056 for a limit of 1.3) but the average waiting time for a Type 1 customer increases by only 4% (from 39.2% to 40.8% of the pipeline length).

Figure 10:8 Average reconfiguration cost multiplier for Type 1 and Type 2 customers, at eight different limits on reconfiguration cost

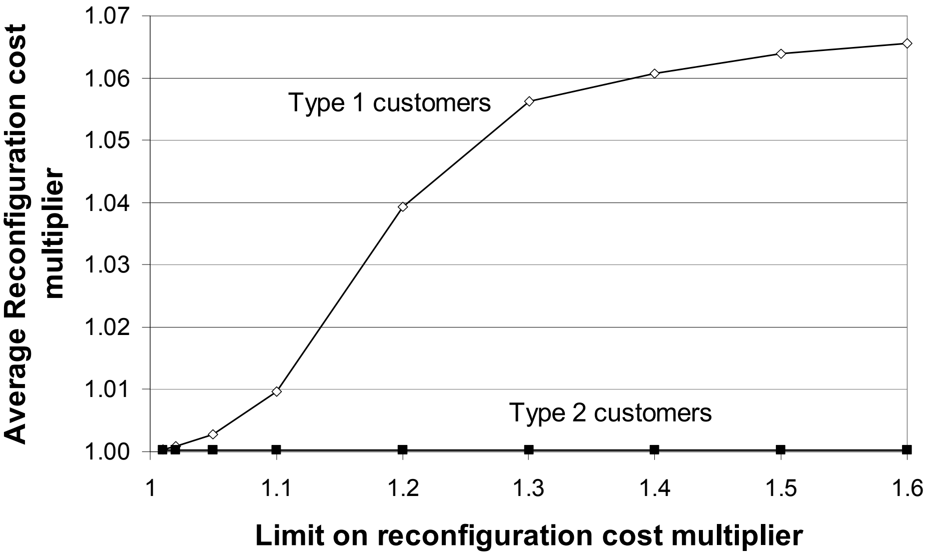


Figure 10:9 Proportions of Type 1 and Type 2 customers reconfigured with and without cost at eight different limits on reconfiguration cost

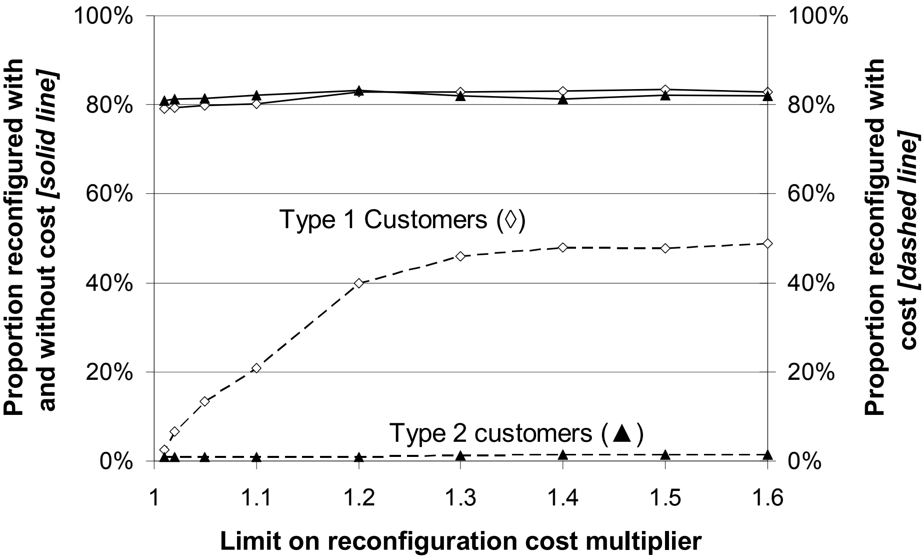
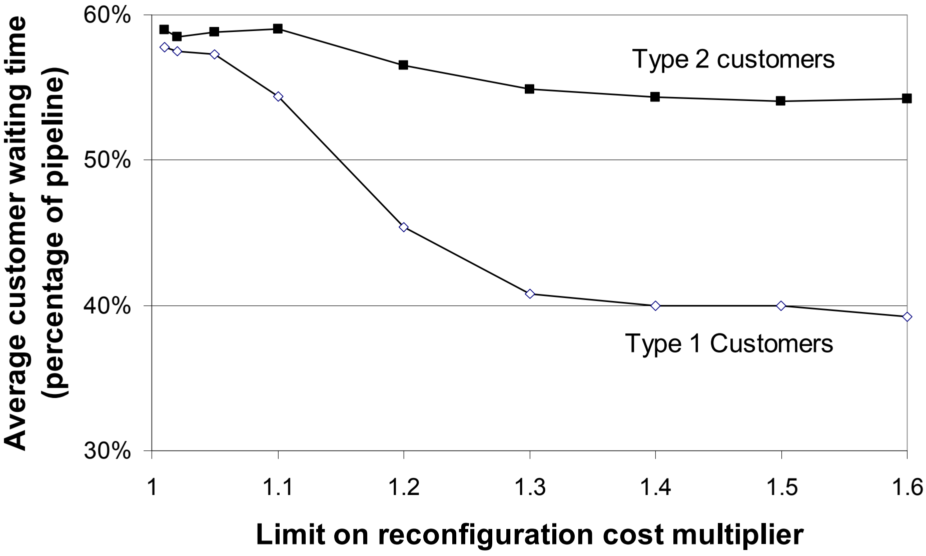


Figure 10:10 Waiting time for Type 1 and Type 2 customers, at eight different limits on reconfiguration cost



10.3.3 Customer mix

Varying the mix of the two customer types reveals how products that are already allocated to customers in the pipeline interfere with the search for products for subsequent customers. Two forms of interference may occur: 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 10:11.

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 10:4) in this zone of the pipeline, hence the matching index in equation [10-3] 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 10:12). 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 10:4) 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 10:11 Waiting time and fulfilment cost multiplier for Type 2 customers as their proportion in the population varies

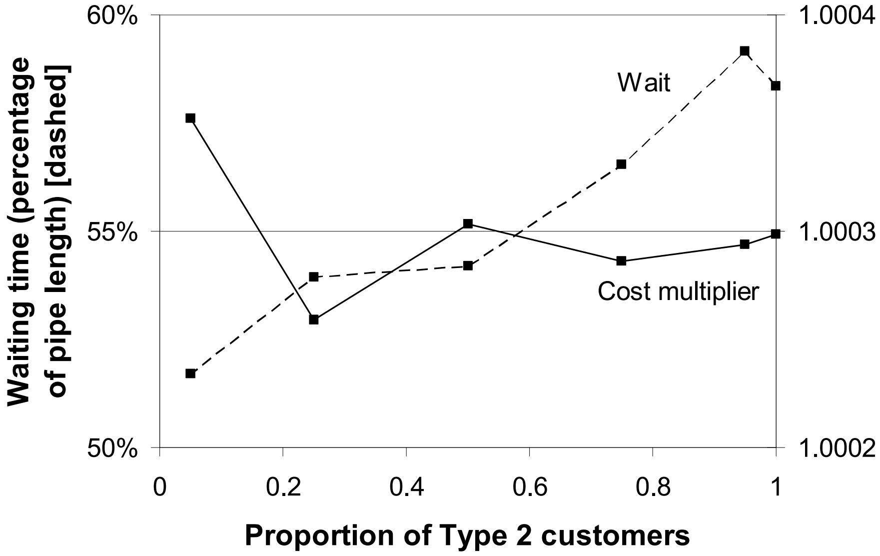
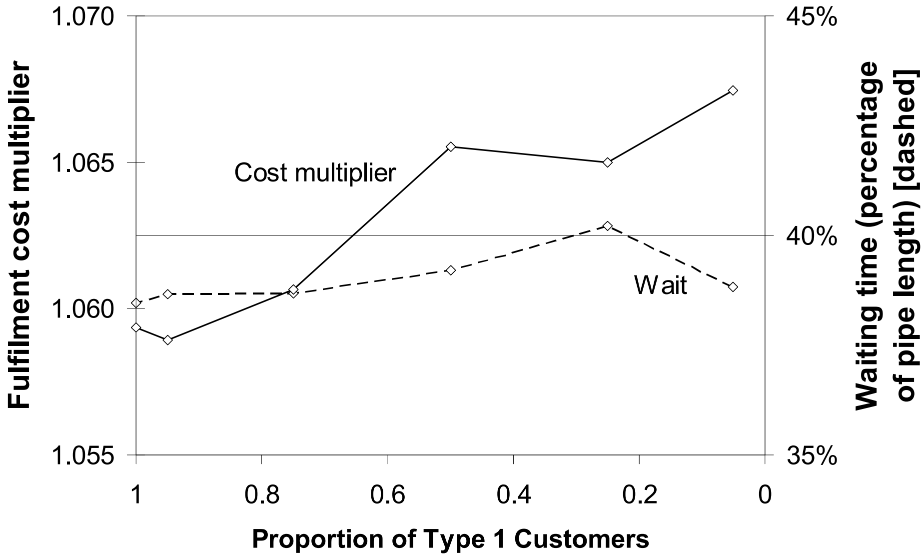


Figure 10:12 Waiting time and fulfilment cost multiplier for Type 1 customers as their proportion in the population varies



10.3.4 Mismatch between produced and demanded variety

In this section there is an equal balance between Type 1 and Type 2 customers but 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 both types of customers is altered with a skew introduced. Five levels of skew are studied (Table 10:2). 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 10:2 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 10:3).

The distribution discrepancy has negatively impacted the customer in terms of waiting time. If the search mechanism were balanced between the producer and the customer, then the producer should also be negatively impacted in terms of the cost of fulfilment. However, the results in Table 10:4 show the cost to rise only slightly for one of the customer types and actually fall markedly at the largest discrepancy for both customer types (condition 5).

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 (in terms of the signature reconfiguration curves in Figure 7:2 on page 59, 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 10:13 Proportions of customers fulfilled through reconfiguration

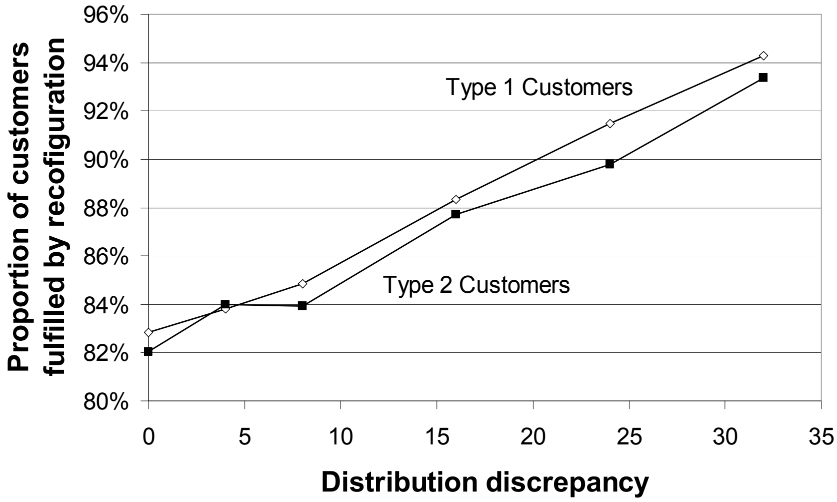


Table 10:3 Impact of distribution discrepancies on average waiting time

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 10:4 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%

10.4 Discussion

In this study it is assumed no customer tolerates compromise in the specification of their product, but that customers differ in their tolerance to 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 when a limit is placed on the reconfiguration cost. It is demonstrated that as the limit is lowered, the fulfilment metrics for the two customer types converge. This result is consistent with the findings from Chapter 9. The performance of the VBTO system is sensitive to external conditions as shown in the studies of customer proportions and variety mismatch. These results are also consistent with the findings from Chapter 9.

Before a producer could implement a search mechanism, they would have to quantify the customer delay aversion functions and the reconfiguration cost curves. The delay aversion functions used in this study have a basis in the theory of exponential value decay but they are arbitrary. An enterprise will need to determine them using a combination of empirical evidence and management judgement. A methodology for doing so, and a methodology for quantifying the reconfiguration cost curves are topics for further research.

Once the functions are quantified, there is scope to adjust the search mechanism. The mechanism used in this study [10-3] favour of the producer, as shown by:

- a 15% reduction in average producer cost accompanied by a 4% increase in customer waiting time when the reconfiguration cost is capped (in section 10.3.2)

- a drop in fulfilment cost but an increase in customer waiting times when there is a mismatch in produced and demanded variety (in section 10.3.4).

A method of adjusting the mechanism may be to introduce a weighting factor, ω, to increase/decrease the contribution of the Reconfiguration Cost Multiplier, as in [10-4].

$$Index_{kj} = \omega.RCM_j \times DA_{kj} \qquad [10\text{-}4]$$

If the mechanism were in balance, an increase/decrease in reconfiguration cost to the producer would be equal to the increase/decrease in value to the customer. In other words, if the producer needs to incur costs in order to shorten lead time, the reduction in customer waiting should make the product more valuable and therefore command a higher price. The balancing of the mechanism is a topic for further study.

Chapter 11
Modelling VBTO systems as Markov chains

Abstract

Preceding chapters used discrete event simulation to model and analyse the VBTO system, but here the possibility of developing a Markov chain model is investigated. If valid it would enable rapid analysis of VBTO systems. An approach to modelling the VBTO system as a Markov chain is developed and the modelling of a 'pipeline only' system shows promise, with apparent agreement between the Markov and simulation results. However, discrepancies between the results when modelling a full VBTO system prompts closer study of the VBTO system, with the conclusion that the Markov conditions are violated - the requirement for 'stationarity' is not met. The cause of this violation is investigated. Consideration is given as to when Markov chain models could be used as satisfactory rapid approximations for VBTO systems. The insights and results obtained from the Markov model increase the confidence in the validity and veracity of the discrete event simulation models used in earlier chapters.

11.1 Introduction

This chapter examines whether the VBTO system is amenable to being modelled as a discrete-time Markov chain. This form of Markov chain is a discrete-state, time homogeneous Markov process, and is used to model a great variety of economic and physical phenomena (Zipkin 2000).

The analysis in section 8.3.1.1 (see in particular page 69) showed the VBTO system cannot be modelled using the Binomial probability model. A cause of the discrepancy was identified as the residence of sold products in the pipeline. A Markov chain model offers a means of developing a probability model that also models product residence.

If the system qualifies as an ergodic process it will be possible to determine the steady-state probabilities from the state-transition matrix. An ergodic Markov chain is one that is irreducible, recurrent, positive and aperiodic (Ravindran *et al* 1987). This would allow average performance of the system to be rapidly calculated by solving a set of linear equations or by taking a sufficiently high power of the state transition matrix to establish the limiting values (which is the approach used in this study).

For the system to qualify as an ergodic process the state-transition probabilities must be stationary, i.e. not be dependent on previous transitions. The model is developed by assuming this is true and the results are used to test the assumption.

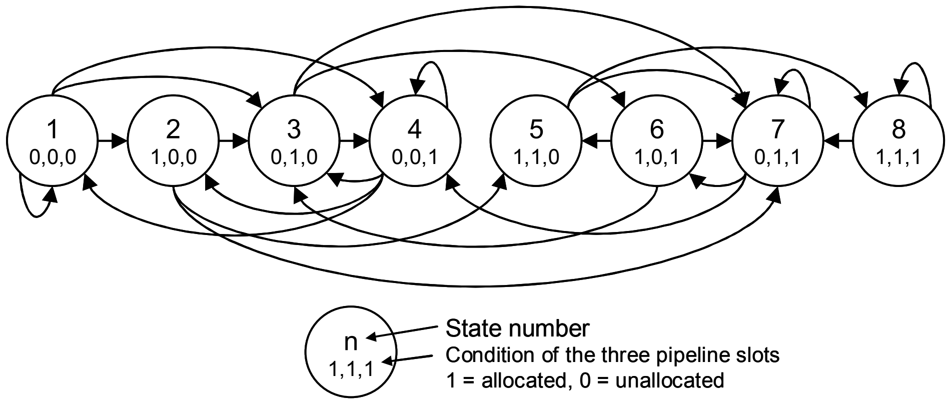
Time can be modelled as being continuous or discrete in a Markov chain with the analysis being more complex for the former. To test the validity of the Markov modelling approach, discrete time models are developed (and the simulations in the earlier chapters are also discrete time models).

The chapter is divided into two with the first part testing the Markov modelling approach on a short 'pipeline only' system, as was studied in section 8.3 (page 68), i.e. the model has no stock or BTO fulfilment and unsold products leaving the pipeline are removed from the system and the customer is unfulfilled. The second half of the chapter presents the findings from modelling a full VBTO system. Again, the heart of the model is a short pipeline, but unallocated products now enter stock and customers can be fulfilled by one of three mechanisms: from stock, from the pipeline and by a BTO product.

11.2 Markov model for the 'Pipeline only' system

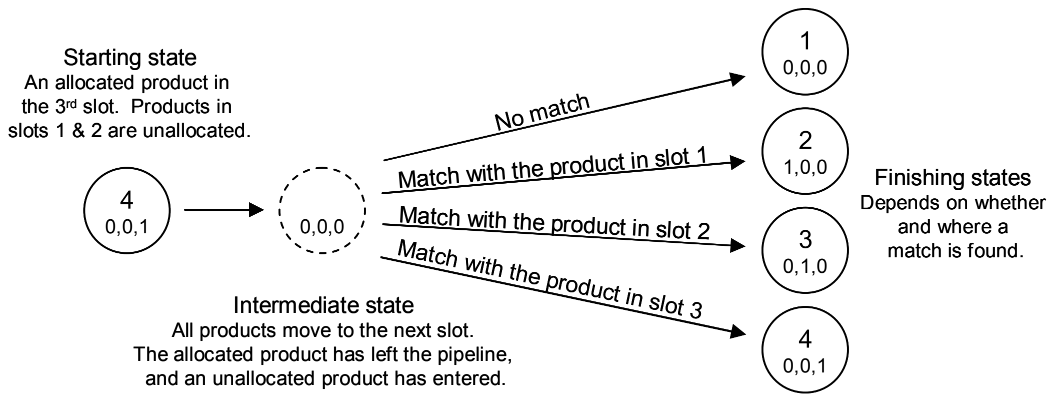
In the first stage of exploring the validity of Markov modelling a model of a short *pipeline only* system is developed. This pipeline has 3 slots for products and as each product can be in one of two states – allocated to a customer or unallocated - the pipeline has 8 states (i.e. 2^3) as shown in Figure 11:1 (in which a '1' indicates an allocated product and a '0' indicates a product that is available, and the products flow left to right along the pipeline).

Figure 11:1 State-Transition diagram showing the pipeline condition in each of the 8 states[26]



The transformation from one state to another involves two events. The first to occur is for the products in the pipeline to shift one place along and the second is for the next customer to search the pipeline. To further explain, consider how the system can transform from state 4 into any of four states. First, the product at the end[27] of the pipeline (which is an allocated product) leaves the pipeline as all products move one place, and an unallocated product enters the pipeline. This is the intermediate state in Figure 11:2. Next a search is made for a match for the next customer. Depending on whether a match is found and in which position it is found, there are four possible finishing states – 1, 2, 3 or 4.

Figure 11:2 Transitions from State 4



To illustrate how the transition probabilities are determined, consider the transformation from state 4 back into state 4 or into state 3. The transition probability from state 4 to state 4 depends on how the pipeline is being searched. If a backward search is used, in which the search begins at the end of the pipeline and proceeds to the start of the pipeline, the system returns to state 4 if the customer matches

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[26] Each circle in the diagram shows the pipeline in a different state, and indicates which of the three products are allocated ('1') or unallocated ('0') to customers

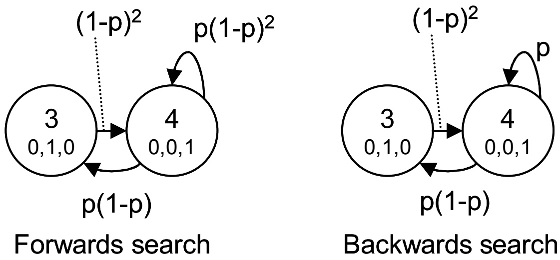
[27] The terminology is identical to earlier chapters, i.e. products enter the start of the pipeline and leave the end of the pipeline

the first product examined. Let us assume that p is the probability of a match[28], then the transition probability from state 4 to state 4 with a backward search is p. If a forward search is used, the transition requires two unsuccessful matches before the successful match, giving a transition probability of $p(1-p)^2$.

In both the forward and backward search methods, the transition from state 4 to state 3 requires an unsuccessful match to be followed by a successful match, hence the transition probability for state 4 to state 3 is p(1-p) in both forms of search.

As a further example, consider the transformation from state 3 to state 4 (Figure 11:3). The transformation involves the products shifting along the pipeline and no match being found between the next customer and the two available products. In both the forward and backward searches the transition probability from state 3 to state 4 is $(1-p)^2$.

Figure 11:3 Transition probabilities between States 3 and 4



11.2.1 State-transition matrix and steady state probabilities

The state transition matrices for the backwards and forwards search processes are presented in algebraic form in Table 11:1 and

Table 11:2 respectively. Only the value of each cell and not the equation in each cell is dependent on the level of variety being analysed. The value of p is 1/n, where n is the number of products in the range.

Once the state transition matrix is quantified the next task is to calculate the steady state probabilities. One method of doing so is to solve a set of linear equations, or, for a small state transition matrix, calculate a sufficiently high power of the matrix such that the limiting values are determined (Ravindran *et al* 1987). This latter method has been used and raising to the power of 3 was sufficient.

Table 11:1 State-transition matrix for backwards search

$(1-p)^3$	$(1-p)^2p$	(1-p)p	p	-	-	-	-
-	-	$(1-p)^2$	-	(1-p)p	-	p	-
-	-	-	$(1-p)^2$	-	(1-p)p	p	-
$(1-p)^3$	$(1-p)^2p$	(1-p)p	p	-	-	-	-
-	-	-	-	-	-	(1-p)	p
-	-	$(1-p)^2$	-	(1-p)p	-	p	-
-	-	-	$(1-p)^2$	-	(1-p)p	p	-
-	-	-	-	-	-	(1-p)	p

[28] A constant value of p is true only if the system is stationary. For this to be true it is necessary, but not sufficient, for the sequence of products entering the pipeline to be independent and uniformly distributed and for the sequence of requests from customers to also be independent and uniformly distributed.

Table 11:2 State-transition matrix for forwards search

$(1-p)^3$	p	(1-p)p	$(1-p)^2p$	-	-	-	-
-	-	$(1-p)^2$	-	p	-	(1-p)p	-
-	-	-	$(1-p)^2$	-	p	(1-p)p	-
$(1-p)^3$	p	(1-p)p	$(1-p)^2p$	-	-	-	-
-	-	-	-	-	-	(1-p)	p
-	-	$(1-p)^2$	-	p	-	(1-p)p	-
-	-	-	$(1-p)^2$	-	p	(1-p)p	-
-	-	-	-	-	-	(1-p)	p

11.2.2 Calculating fulfilment metrics

Once the steady-state probabilities for the eight states are known, the steady-state proportions of customer orders fulfilled and unfulfilled, and the proportions fulfilled from each pipeline slot can be determined. These can be calculated because each transition is associated with a method of fulfilment, as shown in Figure 11:4. There are twenty-four transitions: eight transitions represent an unfulfilled customer order; eight represent fulfilment from position 1; four from position 2; and four from position 3. For example, to find the expected proportion of *unfulfilled* orders, each steady state probability (P_i) is multiplied by the transition probability ($p_{i,j}$) associated with an unfulfilled order):

$$P_{(unfulfilled)} = P_1p_{1,1} + P_2p_{2,3} + P_3p_{3,4} + P_4p_{4,1} + P_5p_{5,7} + P_6p_{6,3} + P_7p_{7,4} + P_8p_{8,7} \quad [11\text{-}1]$$

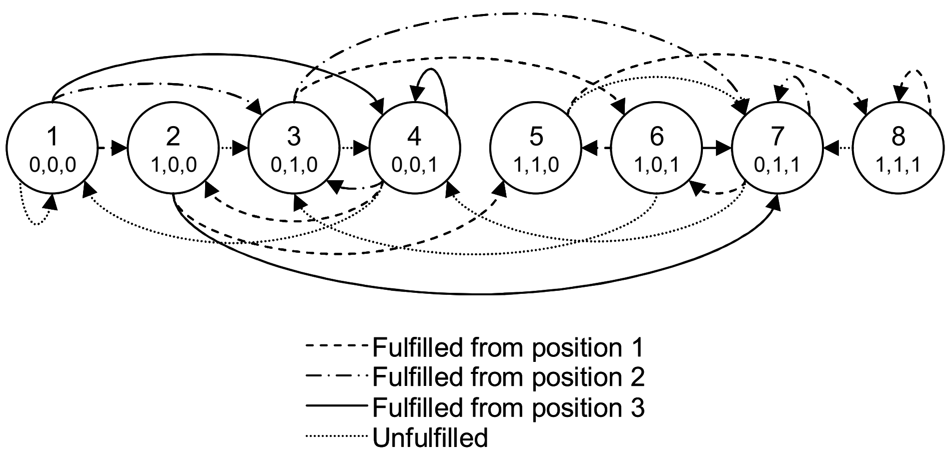
P_i is the steady probability for state i
$p_{i,j}$ is the transition probability from state i to state j

By determining the proportion fulfilled from each position in the pipeline the average customer waiting time can be calculated by [15-2]:

$$\text{Average wait} = \sum_{a=1}^{3} P_{(fulfilled)a}w_a \quad [11\text{-}2]$$

$P_{(fulfilled)a}$ is the total probability of being fulfilled from pipeline position a
w_a is the customer waiting time when being fulfilled from pipeline position a is determined from the pipeline length. In a 3 slot pipeline, the waiting time when a customer is fulfilled from slot 1 is 3 time periods, from slot 2 it is 2 time periods, and from slot 1 it is 1 time period

Figure 11:4 State-Transition diagram with fulfilment outcomes distinguished



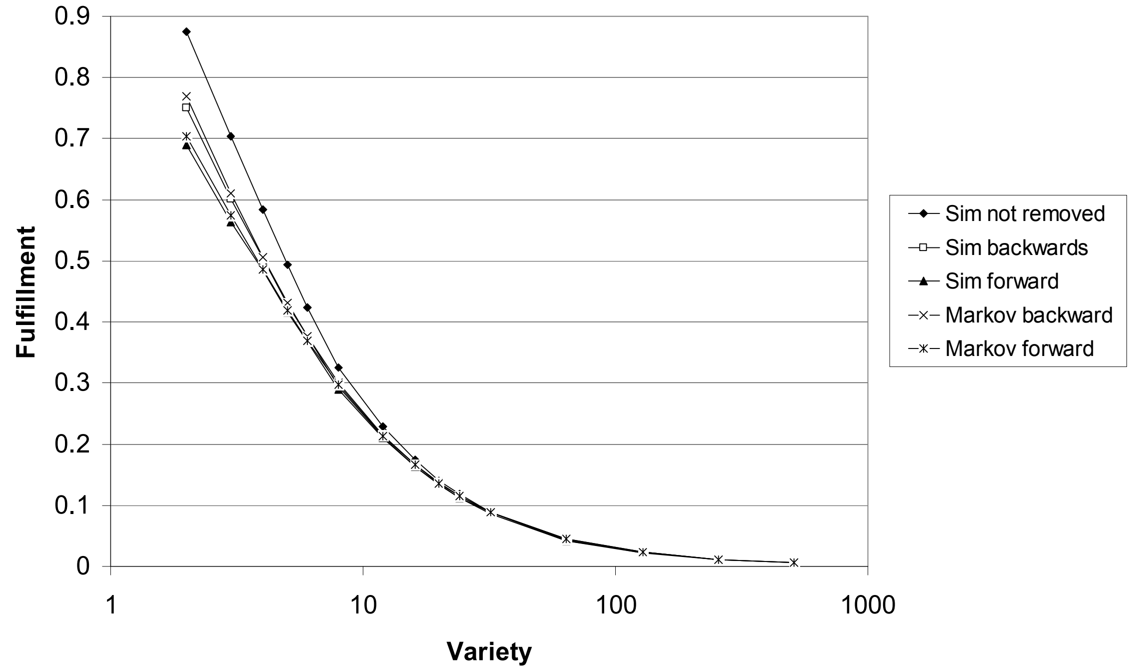
11.2.3 Comparison with the simulation model

To compare the Markov modelling approach to the discrete event simulation, the transition matrices for both forward and backward searching have been quantified for the 3 slot pipeline for product variety levels from 2 to 512. In Figure 11:5 the proportion of customers fulfilled are plotted for the simulation and Markov models and shows close agreement (see section 8.3.1 on page 68, particularly for clarification of the 'Sim not removed' plot).

Figure 11:6, which plots the average customer waiting times, shows a potential benefit of analytical modelling over discrete event simulation, with the analytical model giving precise estimates while the simulation results exhibit measurement error[29]. This plot reveals the average customer waiting time when a backwards search is used is two time periods for all variety levels. When using a forward search the waiting time is dependent on variety, with waiting times longer at small variety levels.

Figure 11:7 demonstrates how the Markov model easily provides statistics on the position from which customers are fulfilled, and shows slots 1 and 3 have identical proportions.

Figure 11:5 Comparison between simulation and Markov model overall fulfilment (pipeline length 3, variety from 2 to 512)



[29] The measurement error for waiting time becomes more pronounced at larger variety/pipeline ratios because, for given length of simulation run, a smaller number of customers are fulfilled as the likelihood of fulfilment tends to zero, hence there are fewer data points used in the calculation.

Figure 11:6 **Comparison between simulation and Markov model of average waiting time (pipeline length 3, variety from 2 to 512)**

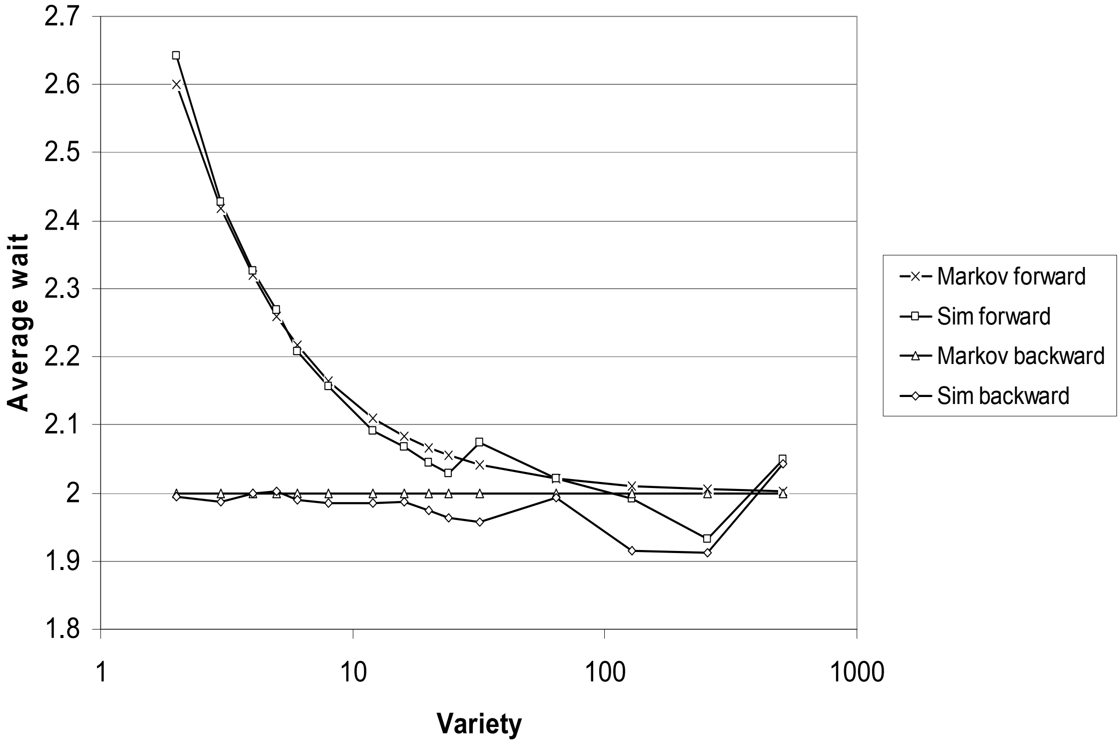
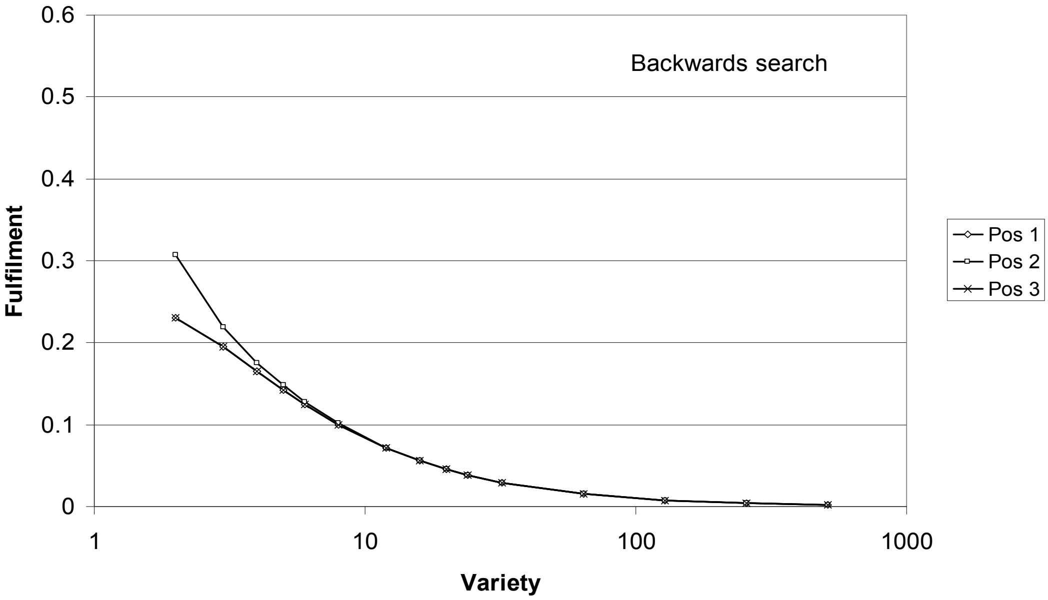


Figure 11:7 **Proportion of orders fulfilled from each pipeline position as determined from the Markov model**

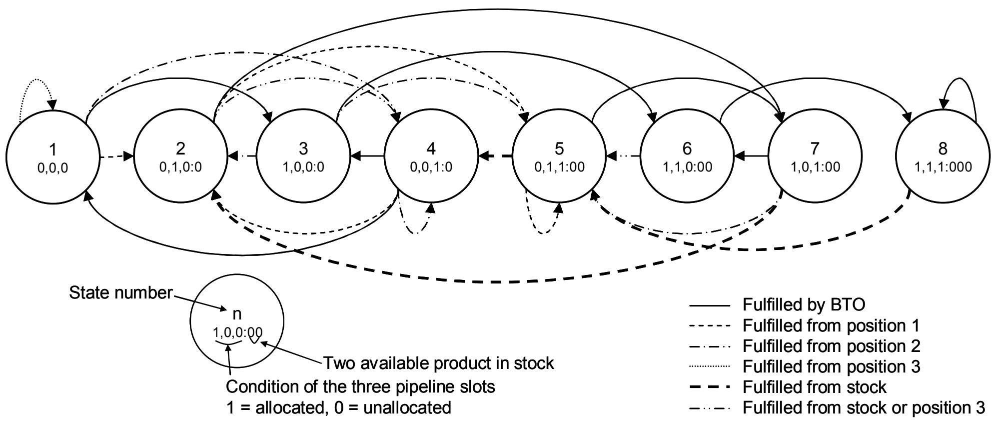


11.3 Markov model for the full VBTO system

In this section a Markov model is developed for the full VBTO with three fulfilment mechanisms – stock, pipe and BTO. A VBTO system with a pipeline length of 3 has eight states as shown in Figure 11:8 in which the fulfilment mechanism associated with each transition is coded. It should be noted that transitions from state 2 to 4, 6 to 5 and 3 to 2 are by either fulfilment from stock or from position 3 of the pipeline.

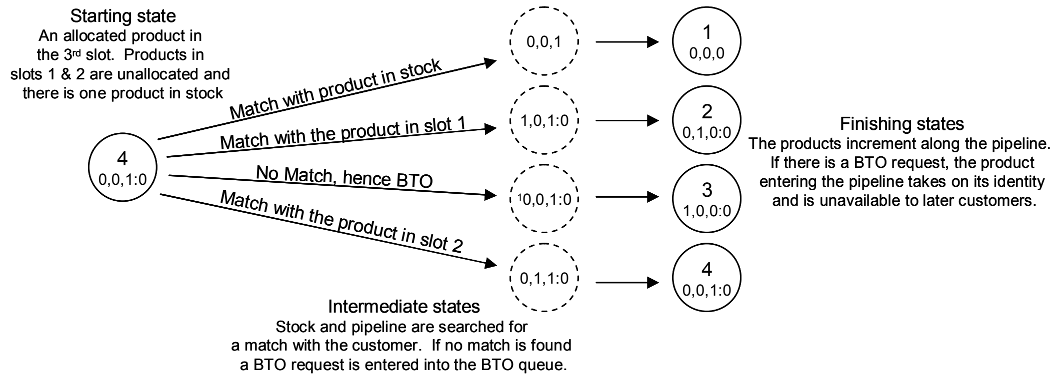
The Markov model shares the characteristic of the simulation models, in that there are fixed number of available products in the system. This is because the customer arrival rate and production rate are fixed and equal. State 1 shows the pipeline primed before the first customer arrives.

Figure 11:8 State-Transition diagram showing the pipeline condition in each of the eight states



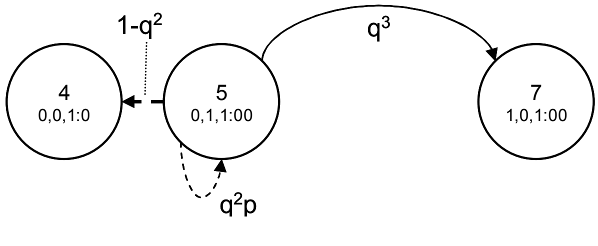
The transition process in the full VBTO system is different from the transition process in the pipe-only Markov model. In the full system the search occurs <u>before</u> the shifting of products along the pipeline. This is illustrated in Figure 11:9.

Figure 11:9 Transitions from State 4



The transition probabilities are calculated in the same way as before, assuming a stationary and constant probability p of a match for all transitions, and q is the probability of no match, i.e. (1-p). Three transition probabilities are shown in Figure 11:10. Using the transition formulae the state-transition matrix is developed to allow the steady state probabilities to be calculated at different product variety levels.

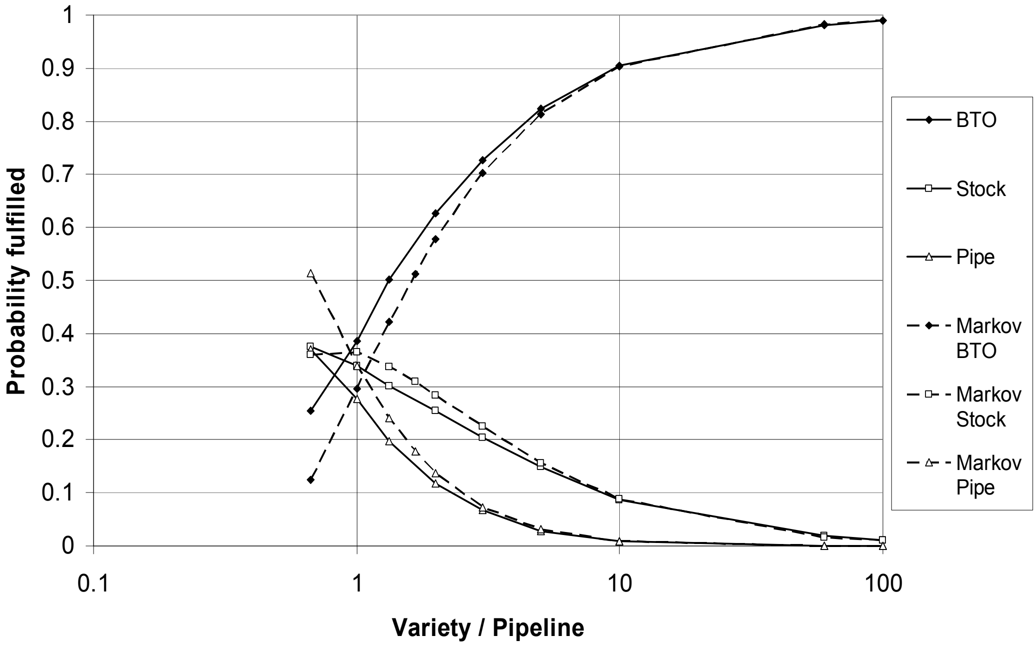
Figure 11:10 Example of transition probabilities (from state 5, Backward search)



11.3.1 Comparison with the simulation model

The results from the Markov are compared to the simulation results in Figure 11:11. There is close agreement between the Markov and simulation models at variety/pipeline ratios above 10. There is discrepancy between the two that increases as the variety /pipeline ratio declines.

Figure 11:11 Simulation and Markov results (Pipeline 3, Backward search)



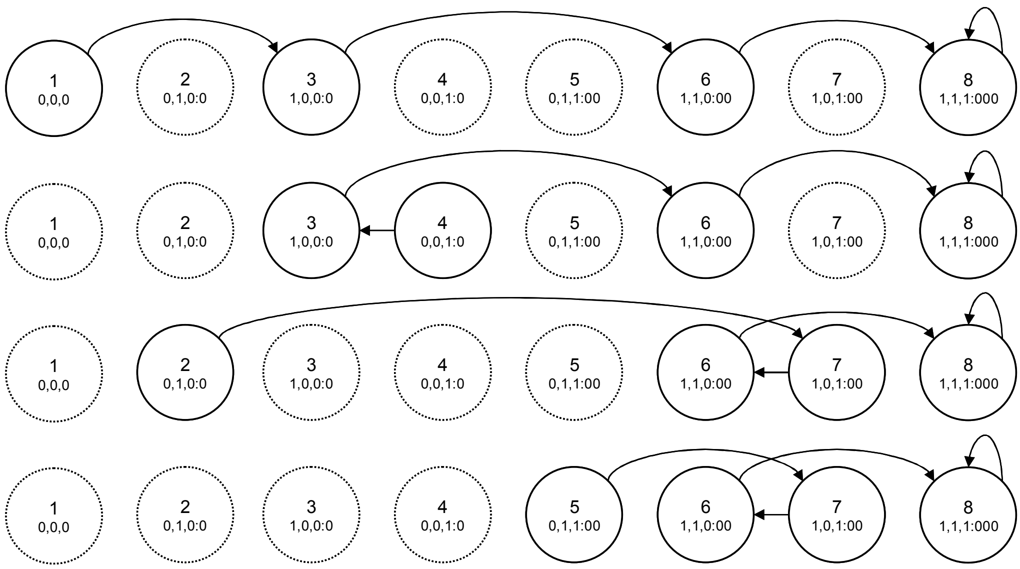
11.3.1.1 Investigation of the discrepancy

The explanation of the difference between the Markov and simulation results has been found through close study of the VBTO state/transition processes, which reveals that it is inaccurate to assume independence between transitions, i.e. the state-transition probabilities are non-stationary and the VBTO system is not ergodic. There is dependence due to the set of searched products being unchanged between customers.

In the VBTO system there are conditions in which the searched set is unchanged or *stagnant*. In each of the four sequences in Figure 11:12 the three available products remain the same. In other words, when the VBTO system follows the sequence of state 1, 3, 6 and 8 the same three products are searched on four occasions without a match being found resulting in a BTO product being fed into the pipeline.

In the VBTO system, transitions 3\6 and 7\6 are always preceded by a search of the same three available products. Transition 6\8 is always the third time the same set is searched, and transition 8\8 is (at least) the fourth time the unchanged set is searched.

Figure 11:12 Four transition sequences with a 'stagnant' set of available products



11.3.1.2 *Matching probabilities in stagnant conditions*

When the sequence of products sought by customers is random and uniformly distributed and they are searching a set of items that are also from a random uniform population, but which will not be refreshed between each search, i.e. *stagnant*, the probability of the first customer finding a match is the same as if it were an independent random search:

Matching probability $= 1 - q^m$

$= 1 - (n\text{-}1/n)^m$ [11-3]

where, n is the number of products in the range
m is the number of products in the stagnant set

If the outcome of the first search is 'no match' then the outcome for the second customer depends on whether the second customer is different from the first. If the second customer is seeking the same specification of product as the previous customer, the outcome must be 'no match'. The probability of the second customer seeking a different specification is:

P(Second customer is different from the first customer) = (n-1)/n [11-4]

The fact that there was no match for the first customer means that the stagnant set can be modelled as being a random set from a population of (n-1) products rather than from a population of n products. Consequently, the probability of the second customer being different from the first, i.e. a unique customer, and of finding a match is:

P(second customer is unique and finds a match) = $(n\text{-}1)/n \times (1\text{-}((n\text{-}2)/(n\text{-}1))^m)$ [11-5]

If the second customer is unsuccessful, the third customer may be successful if different from both the first and second customers. The likelihood of the third customer being different and of finding a match is:

P(third customer is unique and finds a match) = $(n\text{-}2)/n \times (1\text{-}((n\text{-}3)/(n\text{-}2))^m)$ [11-6]

The general expression after i unique customers in a sequence is:

P(customer i+1 being unique and finding a match) = $(n-i)/n \times (1\text{-}((n\text{-}i\text{-}1)/(n\text{-}i))^m)$ [11-7]

This analysis makes it clear that the matching probability is not constant for a sequence of customers if the set of available products is not refreshed. This analysis is verified in Appendix F.

11.3.1.3 *Modification of transition probabilities*

Having identified that stagnation is an issue and therefore that there are dependencies in the sequences of transitions, a basic process for modifying the transition probabilities is developed.

The first stage is to take account of dependencies between a transition and the transitions that immediately precede it. The procedure for doing this is described in Appendix F and the transition probabilities that result for a system with product variety of 4 are given in Table 11:4 which can be compared to the original transition probabilities in Table 11:3.

Table 11:3 Transition probabilities for unmodified Markov model (variety 4)

StartState	End State							
	1	2	3	4	5	6	7	8
1	0.250	0.141	0.422	0.188				
2				0.438	0.141		0.422	
3		0.438			0.141	0.422		
4	0.250	0.141	0.422	0.189				
5				0.438	0.141		0.422	
6					0.578			0.422
7		0.438			0.141	0.422		
8					0.578			0.422

Table 11:4 Transition probabilities for modified Markov model 1: dependencies with preceding transition (variety 4)

Start State	End State							
	1	2	3	4	5	6	7	8
1	0.250	0.141	0.422	0.188				
2				0.431	0.142		0.427	
3		0.417			0.111	0.472		
4	0.250	0.141	0.422	0.188				
5				0.425	0.144		0.431	
6					0.528			0.472
7		0.417			0.111	0.472		
8					0.528			0.472

It was mentioned earlier that in certain transition sequences a stagnant product set would be searched several times. In these cases the transition probabilities are dependent not only on the preceding transition but on even earlier transitions. From examination of the system it is the probabilities of transitions from states 6 and 8 that should be further modified.

The adjustments can be improved by making further modifications for transitions from states 6 and 8. Transitions from state 6 involve the 3rd search of a stagnant set of three products (with transition 6\5 occurring when a match is found and transition 6\8 is when no match is found). The probability for transition 6\5 can be read from Table 11:5 (reproduced from Appendix F) and is 0.485; hence the probability of transition 6\8 is 0.515.

Table 11:5 Probability of a match in the search of a stagnant set of 3, variety 4 (reproduced from Appendix F)

Search	Probability of a match
First	0.578
Second	0.528
Third	0.485
Fourth	0.450
Fifth	0.419
Sixth	0.390

Transitions from state 8 involve at least the 4th search of a stagnant set, and will involve further searches when no match is found. In theory, the system could remain in state 8 *ad infinitum* hence the transition probabilities for state 8 cannot be read directly from Table 11:5. The value for the transition probability for state 8\5 is below 0.45 (which is the probability of a match in the 4th search) and an approximate estimate of 0.35 is used, giving an approximate estimate of 0.65 for the probability of transition 8\8. The impact on the fulfilment probabilities is shown in Table 11:6 which shows the modifications shift them towards the simulation results.

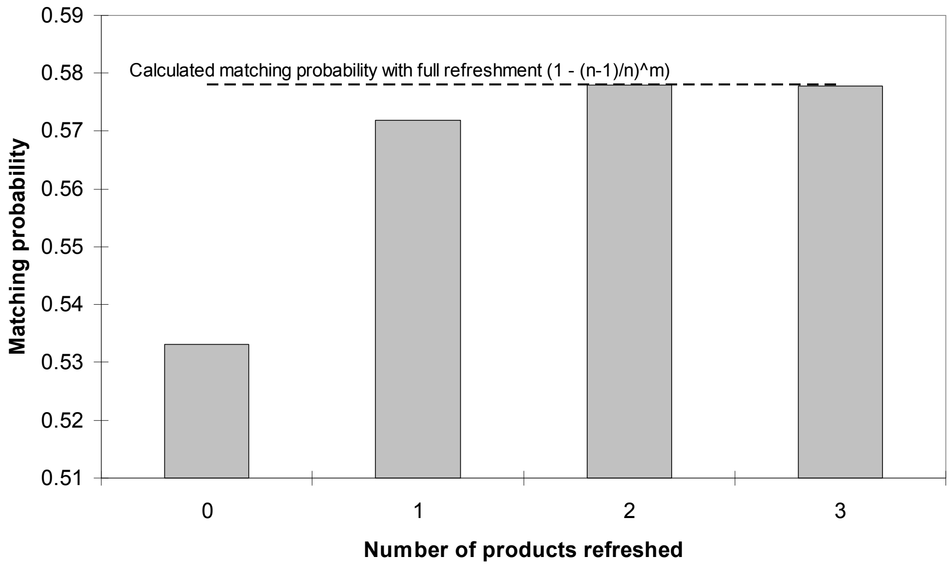
Table 11:6 Outcome probabilities for the simulation, Unmodified Markov and modified Markov models (Pipeline length 3, variety 4)

Mechanism	Simulation	Unmodified (Assumes independence between successive transitions)	Modified 1 (All transitions adjusted for dependence with preceding transition)	Modified 2 (Additional adjustment for greater dependence of transitions from states 6 & 8)
BTO	0.501	0.422	0.447	0.480
Stock	0.301	0.338	0.338	0.322
Pipe	0.198	0.240	0.224	0.210

11.4 Discussion

This analysis leads to the conclusion that the VBTO system does not fulfil the requirements of an ergodic Markov chain. The transition history influences future transitions, hence the system is not memoryless. This is plain to see in the results of the full VBTO model but there is also a suggestion of an error at low variety levels in the 'pipeline only' system (Figure 11:5). The stagnation effect was not immediately apparent in the pipeline only system because the pipeline is not allowed to become stagnant – the removal of unallocated products and the absence of a BTO mechanism ensure at least one fresh product is added before every search. There are circumstances in the pipeline only system when two unallocated pipeline items remain unchanged in successive searches (transitions 1\1, 4\1, 4\2 and 4\3) but a simple simulation shows the impact on the matching probability to be much less than when the pipeline is stagnant. Figure 11:13 shows the effect of refreshment on a set of 3 items when the variety level is 4. The set is stagnant when zero products are refreshed between searches and the searches are fully independent when the number of products refreshed is equal to the set size. The difference between refreshing 2 items between every search and refreshing 3 (i.e. full refreshment) is very small.

Figure 11:13 Matching probability at four levels of refreshment for a set size 3, variety 4



Although it has been identified that the modelling approach is invalid, there may be scope to use it to estimate the performance of VBTO systems. Even without modifying the state-transition probabilities, the Markov model of a short pipeline is accurate at high variety levels. Further work could construct larger Markov chain models to establish the consistency of the error across variety /pipeline ratios.

In developing larger models there is scope to automate both the creation of the state-transition matrix and the transition probability modification process. In this pilot the transition diagram and matrix were developed by hand, but the relationships between states is amenable to formalisation.

The method of modifying the transition probabilities could be further developed and automated. In this pilot exercise, the modification took account of the prior transitions and gave equal weight to all of them. This could be improved by weighting them according to the state probabilities. It may be feasible to develop an iterative procedure, in which:

- step1: the state probabilities are calculated assuming the transition probabilities are stationary;
- step2: the transition probabilities are modified by taking into account the weighted preceding transitions;
- step3: a new solution to the state probabilities is found.

Steps 2 and 3 would be cycled through, stopping (if and) when the state and transition probabilities stabilise.

There appear to be challenges in using Markov chain models in the analysis and design of VBTO systems. It is not clear whether it is an approach that is practical for modelling factors such as reconfiguration flexibility or customer segmentation. These are matters for further research.

Chapter 12
Conclusions

12.1 Conclusions from the operations Modes research

By addressing the five questions in section 2.3 (page 11) the research reported in this thesis has contributed to the understanding of mass customization (MC) as an operations strategy. The empirical case study research has generated a number of new concepts and models to explain product customization and the phenomena of MC. Specifically it has contributed:

- A framework of fundamental operational Modes with five sub-strategies that differ with respect to the way six core operational processes are configured (page 24);
- A model for Mode selection that uses four factors – two internal and two external to an enterprise - to determine when a particular Mode is likely to be suitable (page 29);
- Indicative models of the information infrastructure requirements of two Modes that demonstrate the Modes' different operational implications and requirements (page 32);
- A re-examination of product customization concepts that has generated a set of product customizable attributes revealing the multifaceted nature of customization and extending the terminology of customization (page 37);
- The ∂V (delta Value) concept that relates the motivation for customizing attributes to differences between customers (page 42).

Each is a contribution, but taken together they can be considered to be elements of a theory of MC, which postulates:

1. An MC strategy is relevant when there are differences across customers in how they value the configurations of customizable attributes;
2. There are five operational Modes of MC. Three factors differentiate the Modes, two that are concerned with activities common to all, the first being the temporal relationships between activities, in particular between design and validation activities and other order fulfilment activities, and the second being whether the technological resources used in order fulfilment are fixed or modifiable. The third factor is whether a product is customized on a once-only basis or on a call-off basis;
3. The choice of Mode for an enterprise is contingent on two endogenous and two exogenous conditions.
4. Different Modes have different operational implications and requirements for an enterprise that offers Mass Customization.

A strength of the Modes framework is that it has emerged from observation and analysis. The case study approach has allowed the limitations of existing classification schemes to be uncovered and identified. The Modes framework builds on the existing schemes but has not been constrained by them. A value chain perspective dominates the earlier schemes but has not been adopted for the Modes. Instead they are formed around a process oriented model with six core processes.

12.1.1 Review of the Modes research

Two questions are considered in this review – is the theory that has been constructed a good theory and has the research method been appropriate?

12.1.1.1 *Quality of theory*

In regard to a theory being *good* or *bad*, Wacker (1998) sets out the constituents and virtues of good theory, with the constituents of a good theory being: definitions; domain; a set of relationships and variables; and specific predictions. The theory developed in this thesis has these constituents:

- Definition of MC;
- Definitions of product customizable attributes;
- Definitions of the core operations (variables) for executing MC;
- Relationships between customer value perceptions and customizable attributes (∂V concept);
- Relationships between the core operations processes for specific sub-strategies (the five modes);
- Specific predictions for when each Mode is suitable;
- Specific predictions about the information infrastructure requirements (for two of the modes).

The eight virtues of a good theory are: uniqueness; conservatism; generalizability; fecundity; parsimony, simplicity and efficiency (otherwise referred to as Occum's razor); internal consistency; empirical riskiness; and abstraction (Wacker 1998). It is not straightforward to score a theory against all of these virtues, but the following ratings are suggested for four of the virtues:

- As has been noted, the theory is different from earlier theories, hence it can be considered to have a degree of *uniqueness*.
- As has been demonstrated with the information models, the theory is fertile in leading to other areas and so can map a more interesting space than previous definitions of MC. Therefore it scores well on *fecundity*.
- It is a theory that is good for explaining when MC is relevant, what MC operations involve and how operations are moulded by the market environment. Indeed, the theory accommodates the two views of MC as has been discussed in section 4.3 (page 26). The theory therefore scores well on the virtue of *internal consistency*.
- It is a theory that puts forward specific relationships which make it refutable and hence it scores well on *empirical riskiness*.

12.1.1.2 *Quality of research method*

The second question is whether the research method has been appropriate to the research aims, and has been an approach that has built a valid and reliable theory?

Appropriateness

The aim of this part of the research has been to build theory and for this the case study is recognised as an appropriate tool in management studies (Eisenhardt 1989). Case studies can be used for many types of research and therefore not all forms of case study are appropriate. This research has complied with the recommendations that the case study set should be diverse and that secondary case studies from literature are beneficial. The process of selecting the case studies fell short of the ideal and the set did not contain examples of Modes B and C. This is not felt to have flawed the research but can be addressed in future research to test the theory.

Validity

Validity is concerned with whether the observations and therefore the findings based on them, are linked to the issues and concepts being researched. In general, the more abstract the issues and concepts, the more uncertainty there is over which operational activities and data to examine. In this research the concepts and issues are at a low level of abstraction and the risk of construct *invalidity* is low. For example, the concept of customizable attributes is straightforward to describe and illustrate, and hence the likelihood of collecting inappropriate data is low.

Validity is concerned also with the extent to which findings from a study that is conducted under particular circumstances can be generalised to other circumstances. The size and make up of the case study sample is a factor that can impair external validity. As noted above the set did not contain examples of Mode B and C operations and hence there the external validity is reduced. This is an aspect that can be addressed when testing the theory.

Reliability

At issue is whether the evidence and the measurements are consistent and stable, to the degree that a repetition of the study would bring forth the same findings. As well as increasing the reliability by using a protocol and gathering different forms of evidence, it is argued that there is a low risk of unreliable data. The type of information being gathered from the case study companies was objective and indisputable, and the data collection protocol was robust (for example it did not rely on the careful logging and interpretation of the language used by respondents). For these reasons it is judged that the research is reliable.

12.1.2 Further work

There are opportunities to add detail to the modes theory and to test it.

The identification and study of enterprises that customise one-off products and so fit Modes B & C is clearly an objective for further work. Enterprises that may match these modes have been observed but not studied in depth. An issue for the research to address is the criteria for gauging the 'mass' capabilities of these enterprises, such that they can be differentiated from pure customizers. The research may need to consider whether the working definition of MC needs to be adapted or extended.

In line with the concept of configuration models, the modes framework proposes causal relationships between the five modes and an organisation's internal and external factors. The temporal relationships between core processes have been developed from the case study research, but causal relationships between an organisation's lower level operational details and its MC mode, illustrated by the information infrastructure models (section 4.5, page 32), are propositions. These proposals can be further developed and expanded (a) by developing operational models across the modes, including the remaining information infrastructure models, and (b) by testing these models and thereby testing the explanatory power of the modes framework. To achieve these aims, further case study work can be undertaken to develop operational models from which specific hypotheses can be identified, prior to empirical survey work to test the hypotheses.

Before testing the mode selection framework (section 4.4, page 29), for which an empirical survey method would be a suitable research approach, preliminary work is needed to develop valid and reliable instruments for quantifying and scoring the mode selection factors. A necessary part of this will be to operationalize the four factors since they are constructs and are not directly observable.

12.2 Conclusions from the VBTO research

The second part of the thesis has studied the Virtual-Build-to-Order fulfilment model in detail. The approach has been to explore the model in stages to build an understanding of its underlying behaviour and how production and customer factors impact on performance.

The most important insights and conclusions from this research are:

- the ratio of product variety to pipeline length is a predictor of performance of the system;
- in relation to stock and customer lead time the open pipeline within the VBTO system can lead to significantly different and poorer performance compared to a conventional model which has a closed pipeline, e.g. higher stock levels;
- the ability to reconfigure planned products in the pipeline is beneficial in terms of matching customer specifications, but all customers tend to be fulfilled in the same way even if they are willing to be treated differently. To counter this tendency the producer must implement search rules that distinguish between customers and their needs.

12.2.1 Research achievements

The achievements of the research into the VBTO order fulfilment model are summarised as follows:

- The VBTO system has been positioned within the context of order fulfilment models used for the Catalogue MC mode. Four structural types of order fulfilment model have been distinguished with the VBTO model classified as a system with '*fulfilment from several process points with floating decoupling points*';
- The generic features and concepts of the VBTO model have been elaborated, including:
  - its structure and operational mechanisms;

- the concept of reconfiguration flexibility and reconfiguration cost;
- the concepts of customer aversion to waiting and aversion to specification compromise;
- the concepts of random and common criticality, that describe the behaviour of the customer population when a product has several customizable features;

- A discrete event simulation environment has been developed that has enabled the modelling of different features and configurations of the VBTO model;
- Using the simulation environment the VBTO model have been studied in a systematic manner;
- The VBTO model has been interpreted as a Markov chain, which has allowed further study of its statistical properties.

The concept of *reconfiguration flexibility* is a key contribution. Flexibility, in one guise or another, is a pre-requisite for the MC strategy to succeed (Da Silveira *et al* 2001). Some have spoken of the need for reconfigurable manufacturing resources (Urbani *et al* 2001, Karlsson 2002) and modifiable order fulfilment processes (which are included as a Mode factor in Chapter 4) and others have talked of the ability to physically reconfigure products as a route to MC (Gilmore & Pine 1997). The concept of reconfiguration flexibility accommodates both viewpoints. 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 (e.g. Shewchuk 1999). There are several types of flexibility, such as mix flexibility and scope flexibility, that on first reading appear to be sufficient to describe the qualities of an MC system that make it responsive. It is argued here that the concept of reconfiguration flexibility encapsulates the flexibility required of an MC system. The reconfiguration cost curve operationalises the concept. Quantifying the cost curve would allow MC systems to be compared on a common basis and hence allow the development of a standard methodology for analysing and appraising investment and operational decisions.

12.2.2 Insights from the VBTO research

12.2.2.1 Insights from the discrete event simulation

The insights from the simulation research can be summarised as follows:

- The VBTO system behaves as a complex system, with its performance affected by interactions between external customer factors and internal system factors.
- The variety/pipeline ratio is a key indicator of the fulfilment performance of the VBTO system.
- When the variety distribution is uniform (i.e. not skewed), at variety/pipeline ratios above 10 the VBTO system behaves as a Conventional system (in which the pipeline is inaccessible to customer).
- At ratios below 10 BTO fulfilment is less in the VBTO system compared to a Conventional system.
- When the variety distribution is skewed, in both the VBTO and Conventional systems the dominance of BTO fulfilment is delayed until higher variety/pipeline ratios.
- Aspects of the behaviour of the VBTO system are counterintuitive. Compared to a Conventional system at low and medium variety levels the average stock level and customer waiting time in the VBTO system can be considerably greater even when the feed into the pipeline is in harmony with customer demand and when all other factors are equal. The cause of this is the interaction of sequences of independent and identically distributed random variables.
- In the VBTO system there is greater variation in customer waiting times. In a Conventional system, customers are fulfilled from stock (instantly) or by BTO which requires them to wait the entire pipeline. In the VBTO system customers are fulfilled also from any point along the pipeline. Although average waiting times can be longer in the VBTO system, fewer customers must wait the full length of the pipeline.
- The initial stock level has a significant bearing on the balance between the different fulfilment mechanisms. The greater the initial stock the greater is fulfilment from stock.

- The ability to reconfigure products in the pipeline increases the role of pipeline fulfilment. Only a small amount of reconfiguration flexibility is required to alter the balance between the three fulfilment mechanisms.
- When the customer population can be segmented in terms of their acceptance of compromise, if there is no reconfiguration flexibility the segments will be fulfilled differently, particularly in regard to waiting time. As reconfiguration flexibility increases, the differences in fulfilment reduce. In summary, reconfiguration flexibility allows a heterogeneous population to be homogenised.
- As reconfiguration flexibility is increased, customer waiting time increases due to customers being allocated products from further upstream in the pipeline. The increase in customer waiting can be moderated by incorporating in the search mechanism a customer aversion factor to force the selection of products further downstream. If the cost of reconfiguration is significant, the producer may be able to adjust the search rule so as to reduce average costs while having little effect on average customer waiting time.
- When a product has several customizable features, the producer should spread reconfiguration flexibility across all features rather than focus flexibility on one feature.
- Increasing customer willingness to compromise has a greater impact on fulfilment metrics than reconfiguration flexibility. However, when customers are prepared to compromise in one direction only (e.g. they only accept substitutions and not downgrades), then two-way reconfiguration has greater impact.
- The situation in which all customers share the same perceptions over feature criticality (i.e. common criticality) is more demanding for the producer than when there are differences in the customer population (i.e. random criticality).
- If customers are willing to compromise, the producer can configure the search rule to find the first product that matches a customer's critical features, or to find the product in the pipeline that is the closest match to customer's critical and non-critical features. The former should be used when customers value shorter waiting times more so than specification accuracy, and the latter should be used in the reverse circumstances.
- The producer can impact fulfilment performance metrics, including waiting time by adjusting the feed to be different from the demanded mix into the pipeline. In doing so the producer is exploiting reconfiguration flexibility and the willingness of customers to compromise.

12.2.2.2 *Insights from the Markov modelling*

The insights from the Markov modelling can be summarised as follows:

- The VBTO system can be represented as a sequence of states and state transitions. Each state shows the location of allocated and unallocated products in the pipeline and the number of available products in stock. Earlier comparison of simulation results to a Binomial model had shown that it is necessary to take account of the unsold products remaining in the pipeline.
- The state-transition probabilities are non-stationary. This has been found to be due to the set of available products being unchanged or mostly unchanged between searches. This is referred to in this thesis as 'stagnation'.
- In a small pilot Markov model the error in results between it and the simulation model were largest at the lowest variety level. The errors are small at variety/ pipeline ratios above ~10, suggesting the Markov model is a useful predictive model.
- The error is reduced by modifying the transition probabilities to take account of dependencies between states.
- Further research is required to study the full potential for a pseudo Markov chain model.

12.2.3 *Quality of the simulation model and analysis*

The bulk of insights and conclusions from the VBTO research rely upon the validity and veracity of the simulation environment and on the correct handling and analysis of stochastic simulation data. To address the latter appropriate practice has been followed as described in section 7.2.1.5 (page 66).

An issue is whether the simulation code is a correct implementation of the VBTO system as it was defined in Chapter 7, and that it has remained correct throughout the studies as functionality has been added. Within the research several findings build confidence in the simulation code:

- the basic simulation model recreated the results expected from a binomial model (section 8.3.1.1, page 68);
- when the simulation model was configured in three different ways in respect of reconfiguration flexibility it produced near identical results as expected (Figure 8:14);
- as functionality was added to the model, results were cross checked for consistency with earlier models (e.g. for example see the first paragraph of section 9.3.1.1, page 110);
- the comparison with the Markov modelling approach in Chapter 12 strengthened the confidence in the simulation, particularly as the discrepancy between the two reduced as the Markov model was modified.

The first and last of these points not only verify the logic of the simulation code but are validation against independent modelling approaches, while the other two points verify the consistency of the code.

12.2.4 Further research opportunities

This research has created a platform for further research. There are many avenues to study and aspects to examine further.

Customer behaviour can be expected to be more complex than modelled here. For example, in modelling customer aversion to waiting it is assumed all customers would prefer to receive a product as soon as possible, and that customers differ only in the importance they place on waiting. However, some customers will not want to receive their product before a certain date, such as those who lease a vehicle and who have fixed lease periods. The construct of *delivery date compromise* could be created for this category of customer.

In addition to waiting time, other features of the augmented product could be introduced, in particular price. The option of offering discounts on long lead time products could be explored. This falls within the subject of *revenue management* and the validity of the underlying customer decision making model would be an issue.

The economics of the fulfilment system will be more complex than has been modelled here. In describing the VBTO system in Chapter 7 it was noted that a producer has choices in how a customer is fulfilled. There would come a point where it becomes economic to give the customer a product with substitutions or with redundant features rather than reconfigure a product. This would be a fruitful line of research.

The modelling of stock could be advanced by examining the issue of obsolescence, either by placing a limit on a product's shelf life, or by reducing the price of older stock.

The models used in this research have not included feedback loops to manage or control the mix entering the pipeline. This has been a deliberate approach since the free behaviour of the system can reveal which factors need to be controlled. The stripping of the pipeline described in section 8.4.1.2 (page 84) suggests the system could be complex to control, with the pipeline creating a lag between the point of control, i.e. the feed into the pipeline, and the mix of products in the downstream section of the pipeline and stock. It is likely the VBTO system can exhibit oscillatory behaviour and poor control could cause dramatic swings in the mix. A counter measure could be to insert a product reconfiguration point near to the downstream end of the pipeline, where unsold products are reconfigured in order to maintain balance in the stock mix.

There are opportunities to continue the research on a Markov chain model and to pursue other approaches for developing an accurate analytical model of the VBTO system.

Aside from furthering the modelling of VBTO systems, another avenue of research would be to study reconfiguration within manufacturing enterprises. There is scope to study how reconfiguration flexibility is operationalised (is it by buffer stocks, overtime or flexible processes?), to quantify the reconfiguration cost curve, and to study the relationship between investment and direct costs as conjectured in Figure 7:3 (page 59).

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Appendix A
Case study protocols

A.1 Case study protocols

To follow good practice in case study research a protocol was developed for the purpose of setting boundaries and guiding the field research. Two protocols were developed, one near the start of the research and the second at a later stage, after the development of the set of customizable attributes and the set of fundamental modes of MC operation.

A.2 First protocol

The purpose of the first protocol was to guide the task of becoming familiar with the activities of the case study companies. At that stage in the research it was insights into processes, products and customers that was required, from which theories and models could emerge. As recommended by Remenyi et al (1998) a protocol overview was written (Box A1) that identified the main objectives and issues. A key quotation from the introduction is:

> *'The primary purpose of the familiarisation is to build a repository of observations of contemporary manufacturers, to be used in developing theories and hence principles of mass customisation, along with templates and quantitative models of MC enterprises. With these ends in mind it is without question beneficial to have an appreciation of how manufacturing enterprises produce customised products - how they develop, manufacture and deliver customised products and how they interact with and involve their customers.'*

A.2.1 Extracts from the first case study protocol

A series of procedures were written and two are reproduced below. The extracts presented overleaf are:

- Introduction and guidance;
- Contents; Delivery to customers (example procedure);
- New variant introduction - case study (example procedure).

Box A1: Introduction to the case study manual (continues overleaf)

Introduction and guidance

Within the Mass Customisation research project there is the need to obtain fundamental information about the collaborating manufacturing enterprises. This book of fieldwork procedures describes the scope of profiling, the information being sought, an approach to obtaining the information and methods of presenting the information.

Purpose of the familiarisation

The primary purpose of the familiarisation is to build a repository of observations of contemporary manufacturers, to be used in developing theories and hence principles of mass customisation, along with templates and quantitative models of MC enterprises. With these ends in mind it is without question beneficial to have an appreciation of how manufacturing enterprises produce customised products - how they develop, manufacture and deliver customised products and how they interact with and involve their customers.

All manner of observations could be made. In order to constrain the fieldwork, the theories and models of mass customisation that are emerging in the project have been used to target the data collection. The particular areas these ideas direct the fieldwork toward are:

- the features and properties of the product and/or service that makes customisation feasible and appealing to customers. These could be internal or external factors. Examples include - consumer knowledge, differentiation options, ability to adjust the design to accommodate customer constraints, speed of response to orders.

- how customers are involved directly in product development, order taking and order fulfilment;

- how variety is enabled. Is it enabled by careful design (e.g. modularity) or is it enabled by the versatility of the order fulfilment resources, encompassing suppliers, internal resources and delivery channels?

- operational challenges (or 'overheads') that arise from customisation that a non-customiser wouldn't face to the same extent, such as external or internal constraints, planning and control complexities, additional tasks, supply chain management burdens.

The last category is wide ranging and could be difficult to observe, since it is also concerned with practices the enterprise is not using. For example, the enterprise may not have certain recovery strategies open to it, such as substituting an item from stock when a production upset occurs.

In some circumstances it may be necessary to take a longitudinal view of the enterprise for example before and after a significant strategy implementation such as pre- and post - design for modularity. Recent changes in strategy should therefore be investigated to establish the need to take a longitudinal view of the enterprise.

Criteria for successful profiling

The minimum threshold of success is that an enterprise is understood and the availability of further information, in particular quantitative performance data, is known. If comprehensive quantitative data is collected during the profiling visit, the objectives will have been surpassed. The interviews conducted will be exploratory rather than hypothesis testing. The essential task is to identify the key issues on customisation as perceived by manufacturers.

Output

Information to inform the research topics

Generic operations templates

Overview of the profiling task

The profiling task has four steps:

- on-site data collection (fieldwork)

- formatting of data (off-site)

- initial analysis of data (off-site)

- feedback, verification and validation (participatory presentation or workshop with the enterprise)

It is anticipated that there will be follow up studies with the enterprise to delve deeper into pertinent issues in order to model key sub-systems.

Information gathering structure

The profiling could be structured in a number of ways. For example, a list of topics such as modularity, postponement and customer involvement could have been used. The structure chosen is a generic model of the mass customisation process, with three processes at its core: product development, order taking, and order fulfillment. However, as mentioned above, several emerging models and arguments have informed the prompts in each procedure.

Resources

The on-site data collection is anticipated to require a pair of researchers to be in an enterprise for four to five days, assuming ready access to necessary information and staff. Other resources are listed in the preparation section.

Fieldwork procedures

A set of procedures have been produced to guide the fieldwork. It is intended researchers use the procedures as prompts and aide memoirs, so as to avoid fixation on topics. In general each procedure describes its objectives and scope, the nature of the output sought, the topics and issues of relevance, the approach to obtaining the information and a number of classification variables that can be used. Some procedures also give suggestions on where the data might be found, examples of information, and suggestions on suitable data presentation formats. The familiarisation process is not a survey. Although many procedures include classification dimensions, these are tentative. One role of the familiarisation process is to inform a classification scheme for mass customisation which could be used in a wider survey later in the project.

Box A2: Contents of the case study manual (continues overleaf)

Contents

Part 1

Introduction and guidance

Fieldwork overrview

Guidance on data collection (to be added)

Preparation to go on site

On-site kick-off and briefing

Part 2

Administration procedures

Interview log

Document log

Timetable

New issues log

Part 3a

Detailed profiling procedures

Products and product development

Product family and variant profiling

Product description and coding process by the enterprise

Product design process

Product 'recipe' making process

Variant design process

Variant 'recipe' making process

Customers and order taking

Customer classification

Demand profile

Order taking processes

Post order-taking interaction

Order fulfillment process

Supply of materials and components for customised products

Internal Manufacturing processes - activities and controls

Internal Manufacturing processes - customer involvement

Delivery to customers

New variant introduction - case study

New product introduction - case study

Part 3b

Additional profiling procedures - 'umbrella' issues

Quality systems

Information management systems & Information Technology

Box A3: Example procedure (continues overleaf)

Delivery to customers

Objectives and scope:

Examination of delivery processes from late finishing operation and collation of order to point of customer receipt. Delivery could involve customisation activities by retailers/resellers. The activities they perform, the component stocks and equipment they need, are of interest.

Topics and issues:

How is delivery date and customer identified for the finished product?

Picking from safety stock/customer buffer - identification, FIFO

Items transported by non-standard route i.e. express delivery
Additional rework required to meet customer specification
Understand batching rules of logistics - minimum transportation quantities, collation points.
Warehousing - stock control
Delivery accuracy
Performance measures
On time delivery record
Accuracy of product delivery - product selection / correct delivery address
Customer satisfaction with resellers
Reseller activities
What work is done by resellers, such as assembly
Supply of components
Equipment provided to resellers
Training provided to resellers
Commercial relationship with resellers
Selection of capable resellers
Unapproved customisation by resellers

Box A4: Example procedure

New variant introduction
Objectives and scope:
To map the activities involved in launching a new variant into production. This does not include the design of the variant. Of interest is the time and effort required from the release of the variant to smooth production i.e. order taking, production, scheduling, distribution etc.
Topics and issues:
Setting up information systems for a new variant
Proving the process for a new variant
Sourcing suppliers
Developing procedures for the variant - e.g. quality assurance procedures
Adapting existing or adding new resources - e.g. operator training
Involvement of suppliers
Involvement of customers
Costing a new variant
Collaborative component development with suppliers
Customised components development lead times
Weeding out of old variants no longer required

A.3 Second protocol

After the modes framework and other concepts had been conceived, a second protocol was developed. Whereas the first protocol was designed to facilitate exploration, this second protocol was focused on the issues and topics that were of prime interest to the research. As stated in the introduction to the protocol (reproduced in Box A5):

'The questionnaire allows a profile of an enterprise to be constructed in terms of the mode(s) of mass customization it is currently practicing and an understanding of how its operations are suited and matched to the mode(s).'

The content of the questionnaire is given in Box A6.

Box A6: The Introduction section in the second protocol

Mass Customization research

Mass Customization is a new business strategy with the goal of designing, manufacturing and delivering customised products without losing the economic benefits of Mass Production. Mass Customization must therefore combine customization with high productivity, high quality, quick response and low costs.

Purpose of the questionnaire

The activities and issues explored by this questionnaire are emerging from ongoing research as those that pose challenges and offer opportunities for the implementation of Mass Customization. The questionnaire allows a profile of an enterprise to be constructed in terms of the mode(s) of mass customization it is currently practicing and an understanding of how its operations are suited and matched to the mode(s).

What is a customized product?

The focus of this questionnaire is the manufacture of customized products. A product is customized if any of the following is true:

The customer has been involved in selecting of specifying the design of the product. The customer may have selected from a catalogue of options or made a unique request;

It has been manufactured according to a specification and requirements of a customer (e.g. a customer may have dictated: when it is manufactured, what components are used, how it is manufactured, etc);

It has been packaged or delivered according to the customer's specification. This can include the time and place of delivery.

Box A5: Contents of the second protocol (continues overleaf)

Mass Customization profiling

Mass Customization research

Purpose of the questionnaire

Confidentiality

Filling in the questionnaire

Contacts

About the company as a whole

Product families

About a customized product family

Customers of the product family

Taking an order

Manufacture of the product family

Quality and customer satisfaction

Changes in customization of this product family

Business impact of this product family

About your role

Appendix: Guidance on completing the questionnaire

Appendix B
MC Classification schemes

B.1 Classification schemes

In the development of the fundamental modes of MC operations, six schemes found in the literature for classifying MC are reviewed and applied some of the case studies. Further details of five of the schemes are provided in this appendix[1]:

- Lampel and Mintzberg (1996);
- Alford *et al* (2000);
- Duray *et al* (2000);
- Da Silveria *et al* (2001);
- Pine and Gilmore (1997).

B.2 Lampel & Mintzberg (1996)

Lampel & Mintzberg (1996) discern a continuum of strategies from pure standardization to pure customization:

- Pure standardization: Products are mass produced and the market is treated as homogeneous.
- Segmented standardization: Firms respond to different clusters of buyers, but each cluster remains aggregated. It increases the choices available to customers without increasing their direct influence over design or production. At most there may be a greater tendency to customize the distribution process.
- Customized standardization: Offering the buyer the option to select their own set of components. Products are made to order from standardized components. Assembly is customized while fabrication is not. Might also call this strategy modularization or configuration. Basic design is not customized and the components are all mass produced. Each customer gets their own configuration but choice is constrained by the range of available components. This is sometimes constructed around a central core.
- Tailored customization: The company presents a product prototype to a potential buyer and then adapts or tailors it to the individual's wishes or needs. Customization works backward to the fabrication stage but not the design stage. Modification of standard design for a particular customer.
- Pure customization: The product is truly made to order. Artisans e.g. jewellers, major products and services, including large-scale production machinery. The traditional polarization between buyers and sellers is transformed into a genuine partnership, with both sides deeply involved in each other's decision making.

B.3 Alford *et al* (2000)

Specifically in the context of the automotive industry, Alford *et al* (2000) put forward three distinct strategies of customization - *core, optional* and *form* customization:

[1] There are no further details available for the scheme of Ross (1996)

- *Core customisation*, involving the customer with the design process of the vehicle, occurs in low volume, specialist vehicles. Where the vehicle is designed to meet a specific market requirement, there may be a limited scope for the customer to request changes that affect the core design of the product. Land Rover manufacture classic all-terrain vehicles, with optional features available to the customer to satisfy individual tastes. Beyond offering the classic vehicle, customers may contact the manufacturer to discuss their needs for specific applications and environments. The special vehicles team collaborate with the customer to provide a vehicle based on a standard Land Rover with changes to any of the core elements of the design. Similar collaborations exist between low-volume luxury car companies and their customers, as the nature of the manufacturing process enables customers to modify designs to suit individual preferences. Core customisation is available for low-volume applications at a cost premium to the customer above that of the standard product.
- *Optional customisation* allows the customer to choose their vehicle from a plethora of options, though the design of the vehicle may not be changed in anyway. The customer is integrated into the manufacturing process as vehicles are assembled to their requirements, based on the decisions they make. This strategy differs from pushing excessive variety into the market as the Vehicle Manufacturer is not predicting customer preferences. In addition to the choice of body style and colour, customers select the model of the vehicle to define the standard features, and can supplement these features with options available at a price premium.
- Some features requested by the customer can be incorporated at the distributor. Either new parts are added to the vehicle or standard parts are changed to give the customer the feature they require. This is one aspect of *form customization* - changing the form of the standard product at the distributor. In addition to limited changes or enhancements to the actual vehicle, *form customization* includes the customisation of the terms of sale to the customer. Distributors offer a package of services that help to differentiate the vehicle from their competitors, and tailor the sale to the needs of the customer. These packages include financing options, warranty and service options, insurance and membership with recovery services.

B.4 Duray *et al* (2000)

Duray *et al* (2000) categorize mass customizers by both the stage along the value chain at which customization appears to take place and the customizing method, which centres on product architecture. The work of Lampel and Mintzberg is drawn on to identify the stage along the value chain and the work of Ulrich and Tung (1991) is used for product architecture. Four categories of mass customizes are named – *Fabricators, Involvers, Modularizers* and *Assemblers:*

- *Fabricators* involve the customers early in the process when unique designs can be realized or major revisions can be made in the products. *Fabricators* closely resemble a pure customization strategy, but employs modularity to gain commonality of components. An example of a *Fabricator* is Bally Engineered Structures, a manufacturer of walk-in coolers, refrigerated rooms, and clean rooms described by Pine et al. (1993). Product modules are cut-to-fit specific dimensions of the customer, providing unique rooms manufactured from modular components. Modular components are altered in fabrication to 'fit' the specific building. In addition, unique components may be designed for specific application. Customers are involved in the design and fabrication stage of the production cycle, and component sharing and cut-to-fit modularity are used to provide the mass-customized product.
- Group 2 incorporates customer involvement in product design during the design and fabrication stages but uses modularity during the assembly and delivery stages. Because customer involvement precedes the use of modularity, we refer to this group as *Involvers*. With *Involvers*, customers are involved early in the process although no new modules are fabricated for this customer. Customization is achieved by combining standard models to meet the specification of the customer. Perhaps, the early involvement of the customer imbues the customer with a greater sense of customization or ownership of the product design, although no customized components are fabricated. Because they do not fabricate customized components to customer specification, *Involvers* capture greater economies of scale than

Fabricators while maintaining a high level of customer involvement. An example of this type of mass customizer is Andersen Windows. Andersen uses a design tool that helps customers develop the specific design of their windows. However, products are produced from 50,000 possible window components. Components are not designed or fabricated for the specific application. However, customers specifications are 'designed' and then, the components are selected by the manufacturer to fit this design. The sheer number of components prohibits the customer from simply choosing from a prescribed list, as with component swapping modularity. The customer is involved in the specification during the design and fabrication stages, but the product is assembled from modular components in the assembly and use stages of the production cycle.

- Group 3 involves the customer during assembly and delivery but incorporates modularity in the design and fabrication stages. Group 3, which we call *Modularizers*, develops a modular approach in the design and fabrication stages, although customers do not specify their unique requirements until the assembly and use stage. *Modularizers* use modularity earlier in the manufacturing process than when customization occurs. This modularity may be considered component commonality. In this type, *Modularizers* may not gain maximum customization advantages from modularity. For example, a mass customizing upholstered furniture manufacturer uses modularity in the design of a sofa frame which is used in many product lines (component sharing).This modularity provides for component commonality, but is not used for customization. In the assembly stage, a customer chooses a fabric or wood finish from a prescribed list (component swapping), providing some degree of customization. *Modularizers* incorporate both customizable modularity in the later stages of the production cycle and non-customizable modularity in the design and fabrication stages of the production cycle.
- Group 4 brings both customer involvement and modularity to bear in the assembly and use stages. We call this group *Assemblers*. *Assemblers* provide mass customization by using modular components to present a wide range of choices to the customer. Assemble-to-order manufactures can be considered mass customizers if customers specify products from a pre-determined set of features. *Assemblers* more closely resemble the operations of mass production than the other configurations of mass customers. *Assemblers* differ from mass producers in that the products have been designed so that the customer can be involved in specifying the product. Because the range of choices made available by *Assemblers* is large relative to mass producers, customers perceive the product to be customized. Motorola pagers, a recognized leader in mass customization, can be considered a 'mass standard' customizer. Pagers can be designed to a customer's specification from a wide range of options that are added at the production phase.

B.5 Da Silveira *et al* (2001)

Da Sliveira *et al* (2001) generate eight levels of mass customization ranging from pure customization (individually designed products) to pure standardization:

- Design: collaborative design, manufacture and delivery of products according to individual customer preferences;
- Fabrication: manufacturing of customer-tailored products following basic, predetermined designs;
- Assembly: the arranging of modular components into different configurations according to customer orders;
- Additional custom work: adding custom work to standard products, often at the point of delivery;
- Additonal sevices: adding services to standard products, often at the point of delivery;
- Package and distribution: distributing or packaging similar products in different ways using, for example, different box sizes according to specific market segments;
- Usage: only after delivery, through products that can be adapted to different functions or situations;

- Standardization: no customization.

B.6 Gilmore & Pine (1997)

Gilmore and Pine (1997) identify four approaches to customization, which they call *collaborative, adaptive, cosmetic*, and *transparent*, with collaborative being the one most often associated with the term mass customization:

- *Collaborative* customizers converse with individual customers to help them articulate their needs, to identify the precise offering that fulfils those needs, and to make customized products for them. Gilmore and Pine refer to this as the approach most often associated with the term mass customization. They say it is the customer's inability to resolve multidimensional trade-offs- such as length for width, comfort for fit, or complexity for functionality that has led to collaborative customization. Most collaborative customizers focus on design, but it can be applied elsewhere such as in customizing delivery services where customers specify exactly where, when, and how to deliver goods.
- *Adaptive* customizers create standard goods or services that can easily be tailored, modified, or reconfigured to suit each customer's needs without any direct interaction with the company. The company offers one standard, but customizable, product that is designed for users to alter it themselves. Gilmore and Pine say the adaptive approach is appropriate for businesses whose customers want the product to perform in different ways on different occasions, and available technology makes it possible for them to customize the product easily on their own. They say that if the intrinsic uniqueness of each customer's demands spans an enormous set of possibilities, some form of adaptive customization is imperative and fo on to say that when the possible combinations can be built into the product, adaptive customization becomes a promising alternative to collaborative customization for efficiently making many different options available to each customer.
- *Cosmetic* customizers present a standard product differently to different customers. The cosmetic approach is appropriate when customers use a product the same way and differ only in how they want it presented. Rather than being customized or customizable, the standard offering is packaged specially for each customer. For example, the product is displayed differently, its attributes and benefits are advertised in different ways, the customer's name is placed on each item, or promotional programs are designed and communicated differently. Gilmore and Pine recommend a company adopt the cosmetic approach when its standard product satisfies almost every customer and only the product's form needs to be customized.
- *Transparent* customizers provide individual customers with unique goods or services without letting them know explicitly they have been customized for them. The transparent approach to customization is appropriate when customers' specific needs are predictable or can easily be deduced, and especially when customers do not want to state their needs repeatedly. Transparent customizers observe customers' behaviour without direct interaction and then inconspicuously customize their offerings within a standard package.

Appendix C
Case studies

C.1 Description of the five case studies from the field

Five companies have been studied at first hand and a description of each is given below using the structure of:

- Market and business environment
- Strategy
- Products
  - Introduction of a new customization
- Operations

The data collection methods used in the compilation of the case studies is summarised in Table C1.

Table C:1 Data collection methods

Data collection method	i	ii	iii	iv	v
Interviews	✓	✓		✓	✓
Group interviews			✓		
'Walk-through' of activities	✓	✓	✓		
Inspection of facilities	✓	✓	✓	✓	✓
Structured questionnaire					✓
Self-assessment questionnaire				✓	
Review of documentation	✓	✓		✓	
Review of past studies	✓				

i: European Bicycle company
ii: Computer assembler
iii: Mobile phone manufacturer
iv: Commercial vehicle manufacturer
v: Office furniture manufacturer

C.1.1 *Raleigh Industries: European Bicycle Company*

C.1.1.1 *Market and business environment*

There is an increasing diversity in bicycle types and components. There are bicycles designed for comfort, for road racing, for off-road activities, for stunts. There are bicycles without suspension, with front suspension and those with front and rear suspension. They can have steel, aluminium or carbon fibre components. Component choice has grown, such as with brakes where there are several types of rim brakes and now also disc brakes as used on motorcycles. Furthermore there are many manufacturers vying to be the leading brand for one or more component types.

The number of brands has grown with many being imported into Europe from Southeast Asia as finished bicycles. The SE Asia region dominates component manufacture. The market for bicycles is stratified with the significance of styling features, componentry and the bicycle's properties differing across layers. In general, colour and style are important for lower price segments, componentry becomes increasingly important as price rises, as does dimensional fit and properties of the bicycle (e.g. weight, durability) which are often key concerns at the upper end of the market. The majority of sales are through large retail chains or via small independent retailers where there has been a tradition for bicycles to be customized at the point of sale to a small degree, such as changing the saddle and adding accessories. Mail order companies are a smaller but significant channel.

At present there is an appetite for differentiated products, especially from the mail order companies and larger retailers, who wish to distinguish themselves from other channels. The market is strongly seasonal with approaching a half of all sales coming in the pre-Christmas period.

C.1.1.2 *Strategy*

The company's strategy is to offer to resellers a high level of product diversity to cover the many market segments, and to provide a high level of service in terms of replenishing their stock. Consequently the company is constantly balancing component variety, inventory levels and service performance. It develops a catalogue of products for each segment that is revised annually, though launch periods differ across segments.

The company is prepared to customize 'specials' if expected volumes are sufficient, resulting in customization being limited to larger buyers. No customization is undertaken for individual small retailers. It customizes a product for a period of time, not for a fixed volume. Once the product is specified and designed, that customer can order it as if it were a catalogue model – any time and in any volume. The model is not available to other customers.

C.1.1.3 *Products*

There are approaching 350 products divided across nearly 20 product families. Each bicycle is constructed from around 100 types of components. The number of bought out component lines changes each year, but is in the range of 2000 – 2500. The bicycle has evolved into a modular product (Galvin and Morkel, 2001). The frame is the defining component, but a bicycle is an ensemble of sub-systems with the three main systems being the frame and suspension, braking system and drive system (see Figure C1).

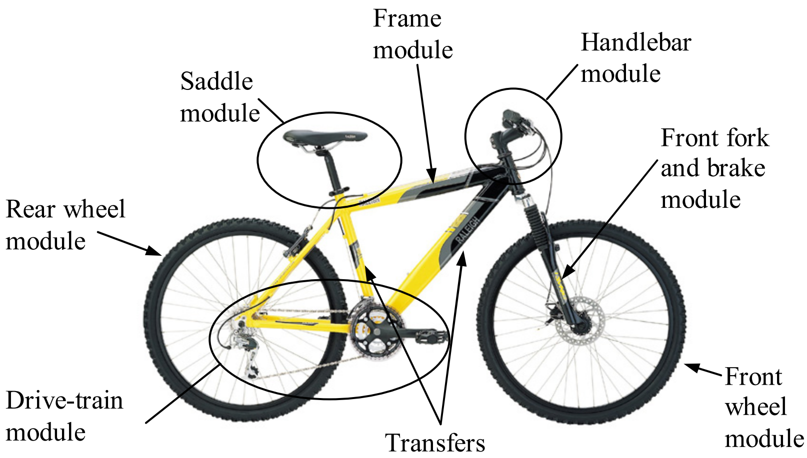
Table C:2 Customized attributes in the bicycle

Attribute	Summary of customization
Hardware function	Suspension choice
Grade	Customization involves selecting grades of components appropriate to the price point
Aesthetics and Style	The painting scheme and graphics are customizable

Introduction of a new customization

Other than for graphic transfers that are used as part of the colour scheme, the company does not source new components for a special product. A typical customization involves selecting one of the standard catalogue products and changing the mix of components and the colour/graphics. Short run specials provide an opportunity for consuming obsolete components.

Figure C:1 Bicycle



C.1.1.4 Operations

The company does not have separate customization resources. Product development, sourcing, manufacture, warehousing and delivery of customized products are undertaken by the same resources as for catalogue products. Orders for customized products are treated just as those for non-customized products and in this company's case the preferred option is to pick from finished stock rather than manufacture-to-order. The production facility does not have the flexibility for small batch production nor is throughput flexibility sufficient to tolerate seasonal demand undulations even with seasonal staff being brought in for peak periods. The extent to which temporary staff can be used is limited due to many assembly tasks requiring skill and experience to achieve the quality at the fast production rate.

Manufacturing is a batch process, with batches from 30 to 100. The process is divided into areas, including component warehouses, wheel assembly, frame and fork painting, final assembly, finished stock warehouse. A synchronous line is used for assembly with tasks of equal cycle time. Throughput is of the order of 500k units per year. There are two main barriers to lowering the batch size - the time to 'pick' components and the painting operation. It takes over an hour for a person to pick the components for a batch of 100, and only a little less time to pick for a smaller batch. For painting, the frames are hung on a moving line that passes through one of two painting booths. The time lost in changing colour precludes small batches.

Figure C:2 Assembly area and frame paint conveyor[2]

Initial inquiries for specials are not handled through the routine ordering mechanism, but via a Product Manager or a member of the sales team. Product development, sourcing, manufacture, warehousing and delivery of customized products are undertaken by the same resources as for catalogue products. Once the customized product is designed and made available to the customer it is

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[2] Pictures from: http://news.bbc.co.uk/1/hi/programmes/working_lunch/education/1552145.stm

assigned a product number and that customer can place orders for it just as for any other product from the catalogue.

Sales of specials are forecast and purchasing and production planned accordingly, as for catalogue models. Order sizes are often in single units delivered to a specific outlet. Week-on-week variation in the demand for a product, whether a special or a catalogue item, tends to be high.

C.1.2 RM: Computer Assembler

C.1.2.1 Market and business environment

A 'sell then produce' business model has evolved in this sector therefore build-to-order is an important competency. A make-to-stock policy would run the risk of product obsolescence due to short component lifecycles. The market is very competitive and manufacturers are vying to offer the best specified machine at a set of common price points. Being quick to introduce latest components is important.

C.1.2.2 Strategy

This company is targeting specific selected sectors where the supply of IT services and software is as great or of greater importance than the supply of hardware, but where the ability to customize the computer offers advantages. For example, a significant proportion of customers appreciate receiving computers that are configured for their network with software pre-installed.

Customers fall into several segments, which differ in terms of the services and service performance offered. In respect of the computer manufacturing division, this translates to different lead times per segment. There is strong seasonality in the sales with two high activity periods. The throughput difference from highest to lowest month can of the order of nine times. The assembly process has been designed to provide the necessary level of throughput flexibility by taking on seasonal staff as necessary. Assembly tasks are not complex and can be learnt quickly, with high quality achievable under vigilant supervision.

C.1.2.3 Products

The company assembles and configures desktop computers and servers. It configures the software on Notebook computers but otherwise does not alter them.

A desktop computer is constructed from, typically, 20 to 30 components. In most cases customers select configurations of memory, processor type and so on to suit their budget. The other routine type of customization is the selection of components to conform to the customers existing systems such as choice of network card.

Although a significant proportion of the computers assembled have unique configurations (20%) there is high commonality of components, as configurations can be different in one or two respects. Consequently the variation in demand of components is low even if there is high variety in the manufactured specifications. Shortfalls in components can be overcome by recourse to wholesalers.

Changes to components are frequent, requiring a systematic product change process to log changes and prompt revalidation.

Table C:3 Customized attributes of a computer

Attribute	Summary of customization
Hardware Function	Examples include: selection of equipment such as soundcards, networking cards; inclusion floppy disc drive
Software Function	Selection of operating systems, utilities and packages
Grade	For example: capacity of RAM, disc drive capacity; CD writing speed
Packaging	Choice of peripherals

Introduction of a new customization

At any one time there is a catalogue of options from which customers select. This is constantly revised due to the short lifecycle of components. Changes to the catalogue are controlled through a change procedure that requires components to be reviewed and validated before being added. Interactions between components can impair product performance hence the need for a structured validation process.

It is very rare that customers request components that are outside of the catalogue, normally due to a technical requirement. These are handled outside of the normal product validation procedures.

Figure C:3 Desktop computer from RM[3]

C.1.2.4 Operations

Order taking is direct via a number of methods – web, telephone, sales person. Integration of information systems enables availability of components to be checked at the time of ordering. Order size is from one to tens and upwards. Customers can change the specification up until the point of manufacture and can check on progress.

The manufacturing schedule is extremely flexible. Orders are prioritised and the highest priority are skimmed from the system several times an hour. Routines within the planning software revise the priorities automatically with the aim of fulfilling each order within the promised delivery time.

Assembly is organised in parallel mini-lines which feed a burn-in and software loading cell, and onto final testing, packaging and despatch. Each product is given a unique job number and its progress is controlled by a central database, which uses the customer's specification to determine the BOM, software loading and testing regime. Components are picked for each machine in turn and handheld scanners are used to log each component picked, enabling the manufacturing control system to alarm when errors are made.

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[3] Picture from: http://www.rm.com/he/products/Product.asp?cref=PD117541

Although assembly time and duration of tests vary with the configuration no restriction is placed on the sequence of computers through the assembly and test areas since the processes can tolerate the variation.

In the packing and despatch areas all other items such as keyboard, monitor, manuals etc are picked for the order. Staff are linked to the central database which navigates them to each item.

C.1.3 Ericsson: Mobile phone manufacturer

C.1.3.1 Market and business environment

Mobile phone handset manufacturing facilities serve global markets, with international supply chains and despatch to customers worldwide. Consolidation in the mobile telecommunications market means network operators are also global and powerful. However, manufacturing competition is very strong with competitive factors being product customization and not least, production costs.

C.1.3.2 Strategy

This company has several manufacturing facilities, supplying network operators around the world. Each product is sold to many customers, and is manufactured on a make-to-order basis as far as possible, but any slack time is used to replenish a central warehouse with high demand models. It is imperative the manufacturing function is responsive to customers. At times this conflicts with the company's desire to have its products retain their brand identity, such as when a customer demands the packaging be in their livery.

C.1.3.3 Products

The product is the mobile handset, the box and its contents which includes manuals and, occasionally, promotional materials. The customizable attributes are: the body of the handset, which can be in single or dual colours; the flip down front on which a customer's logo can be printed (8 variants of colour and logo combinations are in production); software of the handset (over 600 variants); the antenna (no customer has chosen to make this a distinct colour from the body); labelling on the body (in accordance with product safety regulations); and the packaging (size of box and contents).

Introduction of a new customization

To protect against a new variant being problematic to manufacture its bill of materials is checked on paper and a test product may be sent through the facility. This tests the processing of components as well as the control systems, and an example of a problem uncovered was when a robot cell struggled to drive a screw into a body of a new colour. A request from a customer for a new software variant can be implemented in a couple of days. Other customizations depend on supplier responsiveness.

Table C:4 Customized attributes of the mobile phone

Attribute	Mobile phone
Software Function	Many possible customizations including: menus, functions, language
Aesthetics and Style	Colour of the body and antenna
Identification and Personalization	Logo's can be added
Literature	Document and manuals can be customized; labelling on the handset for product safety regulations
Packaging	Size of box and contents

Figure C:4 The T20 handset[4]

C.1.3.4 Operations

Worldwide orders are collated centrally and allocated to the manufacturing facility. Order size varies from a few (less than 10) to many thousands of handsets. Throughput at this facility is in the order of 6 million handsets per year.

The body colour is determined at the first stage of manufacture, as the body provides structural support to the internal electronics. The handset is assembled by a sequence of robots. A buffer of different coloured semi-finished phones is held at the decoupling point. Up until this point the product is tracked by batch.

To fulfil an order the semi-complete handsets are taken from the buffer to have the appropriate flip cover and antenna attached, software loaded and labels put on. At this point the handset is given its own identity. Finally the box and contents are assembled in readiness for the handset. Apart from software loading all of these tasks are manual.

The final assembly operation is flexible and there is the ability to handle batches of one though it is unusual for a batch to be less than 4 handsets. Flexibility is needed for customized packaging in particular, as customers have requested their own specification of box as well as literature. On occasion a customer requires promotional items, with an example being a hat, to be inserted.

C.1.4 Ford Transit: Commercial vehicle manufacturer

C.1.4.1 Market and business environment

Since the introduction of commercial vehicles the number of manufacturers and choice of products has grown greatly and competition is significant. It is the norm for a manufacturer to offer extensive choice over length, height and layout as well as over other factors such as engine capacity, decor, etc. For many customers this level of customization is sufficient. However, there are large numbers of bodyshops that customize vehicles in the aftermarket, with the capability to add a company's livery through to radical structural alterations. Some of these customizations can be extensive and involve installing special equipment, removing unwanted components, fitting internal racking, or putting a different body on a chassis. Examples include vehicles for emergency / recovery services, vehicles with articulated loading systems and vehicles for carrying livestock.

C.1.5 Strategy

As well as offering a wide range of standard choices, this company sees benefit from gaining a share of the special customizations being performed in the aftermarket. The fleet market is significant and customization capabilities can influence a fleet manager's buying decisions. Their requirements can be diverse and a pre-engineered range of options may be insufficient, hence the company has chosen to offer a *specials* customization service. It has formed close relationships with several bodyshops who collaborate in the design process as well as the production of specials.

[4] Picture from: http://the3gstore.mobiles.co.uk/sony-ericsson-t20-accessories.html

An advantage to a customer of having the OEM lead the customization is greater quality control and consistency in the product. Previously a fleet operator may have had to co-ordinate and manage several bodyshops, giving rise to different solutions of varying compatibility.

The company prefers not to take on a 'special' unless there is an expectation of the customer purchasing a sufficient number of them to cover the engineering and mobilisation costs. However it has no hard and fast rules and each request for a special customization is reviewed on its own merits and in light of the relationship with the particular customer.

C.1.5.1 *Product*

The commercial vehicle is designed to be configurable with many options. The vehicle has a number of wheelbase lengths, heights, and drive-train options (e.g. fuel type, front or rear wheel drive).

Table C:5 Customized attributes of the commercial vehicle

Attribute	Example customizations
Dimensional fit/size	Length and height
Hardware Function	Addition (or removal) of equipment
Property of the whole product	Noise emission, cold starting capabilities
Grade	Material grades
Aesthetics and Style	Paint, colour co-ordination of parts
Identification and Personalization	Livery, logos

Figure C:5 Transit vans[5]

Introduction of a new customization

There are two routes for a new customization to be introduced. One is for it to be engineered through the 'standard' catalogue process. The second is for it to be engineered through the 'specials' process which is prompted by a customer. To initiate a special product, customers can approach dealers but in most cases they go straight to a dedicated liaison team in the company. The engineering may require a partner bodyshop to be involved.

The engineering process involves cross checking for clashes between a modification and other options and the assessment is recorded in the product's master configurator. One of the difficulties of managing specials is that they can be affected by subsequent modifications or updates to standard features and hence can require revision and revalidation.

Special customization can involve: external livery, seating arrangements, modification of electrics, addition of aerials, special racking systems, addition of anchoring points, or the fitting of a unit onto the chassis.

Expertise from the customer may be necessary, such as for fitting electronics and aerials. In some cases end-user needs are not straightforward to interpret and the first product is treated as a prototype.

Once a special has been engineered and added to the product catalogue a customer can order it in the same manner as ordering a standard option. As far as possible the special options made are available to all customers.

[5] Picture from: http://www.ford-van.com/index.html

C.1.5.2 Operations

Vehicles with standard customizations (i.e. from the catalogue only) are scheduled as build-to-order products for customers or dealer stock orders. Special customizations make up approximately 15% of production.

The production is divided between a traditional automotive assembly line using synchronised track followed by finishing work at a bodyshop. A minority of specials involve additional tasks on the assembly line only, but the majority have additional tasks on the line as well as bodyshop work.

Sequencing constraints are imposed in order to balance the assembly process.

C.1.6 Orangebox UK: Office Furniture Manufacturer

Orangebox is a provider of office furniture solutions. The company has a turnover in excess of £16million with 120 employees and head office and factory in Hengoed, Mid Glamorgan. In 1999 the company won the Management Today Best UK Small Factory Award. The principal areas examined were lead times, flexibility, efficiency, training, inventory, development facilities, productivity and delivery. The assessment noted that Orangebox uses '*simple flows and systems to take a relatively complex product and make it both manufacturable and profitable*.'

C.1.6.1 Market and business environment

The office furniture market is competitive and there are many drivers for high product variety and customization:

- Corporate image and branding, such as furniture for retail environments;
- Multi-zoned workplaces, with the trend towards distinct areas for task work, meetings, visitor reception, break-out zones and conference presentations;
- Employee welfare concerns such as back pain and repetitive strain injuries that can be exacerbated by seating and workstation design;
- Technical demands of work environments such as durable seating for 24/7 use of anti-static options in hazard control areas.

C.1.6.2 Strategy

The company is positioning itself as a B2B office solutions provider and offers technical support services as well as supply and on-going service support of its products. It believes the ability to customize its products and produce a very high variety of products in batches of one, without losing efficiency, is a business advantage. This improves its ability to support its customers who will need not only bulk supply to a new office but occasional addition or replacement of individual products.

The company has invested to automate many areas of business activity:

- £600,000 investment in a fully integrated IT system that has streamlined processes from order entry and processing through to purchasing, inventory control, production and finally shipping and finance. This includes EDEN Order configuration software and Fourth Shift MRP II Manufacturing System;
- £100,000 investment in a CNC cutting machine that has increased productivity and maximised fabric utilisation;
- £80,000 investment in 3D CAD technology that has cut development time by 35%.

C.1.6.3 Product

Orangebox has 50 product families with 278 base models. Customization of products is routine and the modular concept is used within product families to ensure there are common assemblies, common fastenings and common interfaces so as to reduce parts and enable fast and reliable manufacture.

Its biggest selling product is the g64 task chair which is configurable in many ways over and beyond the adjustable features built into the design. Customers select from: 4 back sizes; 3 seat sizes; 8 castor options; 3 base options; 2 gas-lift options; 2 mechanism options; 6 arm options; 4 upholstery options; 3 coat-hanger options. In all there are over 80,000 possible combinations of options. On top of this 3000 standard fabrics are offered in various arrangements or a customer can have the chair upholstered in a fabric they source themselves (approximately 25% of g64 products are upholstered in the customer's own fabric).

Table C:6 **Customized attributes of the g64 range**

Attribute	Summary of customizations
Dimensional fit/size	Customizations include backrest height, seat width, and chair height
Hardware Function	Movement options such as: static, swivel, castors, armrest, coat hanger
Property of the whole product	Heavy duty options for chairs that are used in 24/7 environments
Quality grade	Grade of fabric
Aesthetics and Style	Choice of surface finishes and fabric combinations
Personalization	Logos can be added
Literature	Choice of how the literature is attached to the product (in a pocket or hanging)
Packaging	Packaging is tailored for some customer

Figure C:6 The g64 product family

Introduction of a new customization

The product range offers sufficient options for there to be almost no need to add new customizations to the product. The company's assessment of the fit between the amount of customization in the product and the amount demanded from its customers is summarised in Table C7. For no attribute does the company feel it offers insufficient customization.

Very occasionally requests are received for non-catalogue options such as changing the surface finish of a component. These are considered on their own merit.

Table C:7 Orangebox assessment of customization demand in reference to amount of customization offered

Customizable attribute	Is the customization potential of the product more or less than demanded by customers?		
	More than	Correct amount	Less than
Dimensional fit/size		✓	
Hardware Function		✓	
Property of the whole product		✓	
Quality grade	✓		
Quality level		✓	
Aesthetics and Style	✓		
Personalization		✓	
Literature		✓	
Packaging		✓	

C.1.6.4 *Operations*

Orders are taken by phone or salesperson. A product configurator guides the order taking process which gives an instant assessment of the anticipated margin. Algorithms make use of information including: product specification, product range, sales channel, contract terms, order value and number of units in the order to calculate the cost and margin for the order. The method is accurate to within a couple of percent.

Orangebox has organised its supply chain and order fulfilment processes to be flexible and responsive. It is producing approximately 2000 g64 units per week and achieving an average lead-time of three weeks.

The g64 is produced under licence from the Swiss company Giroflex and Orangebox could source components from the continent, but the benefits from short replenishment cycles and closer relationships are such that they have invested in tooling and opted for UK suppliers. A total of 56 stock turns per year has been achieved;

The majority of manufacturing is in batch of one (Table C7). Work in progress and finished stock are low, with two hours of WIP and four hours of production awaiting despatch (twice daily).

Table C:8 Batch size distribution

Batch size	Proportion of batches (%)
> 5	21
5	3
4	5
3	6
2	14
1	51

Figure C:7 Fabric cutting, sewing and chair assembly[6]

[6] Pictures provided by Orangebox UK

Appendix D
Data flow diagrams

D.1 Data flow diagrams

The information infrastructure is represented on a Data Flow Diagram (DFD) due to the strengths of the DFD method to summarise a whole system in one diagram.

In structured system analysis methodologies such as SSADM (Ashworth and Slater, 1992) DFD are part of the Data Flow Modelling stage, the objectives of which are to:

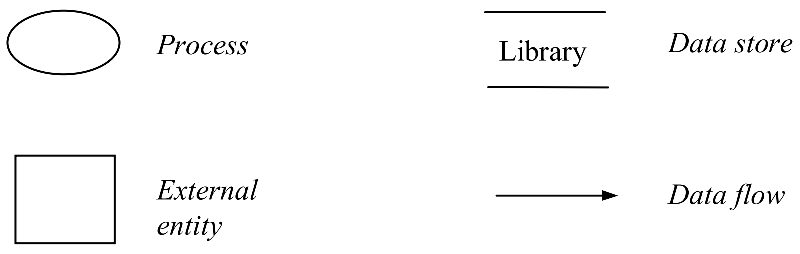
- Understand the flows of data around the system;
- Define the processes that transform or manipulate the data;
- Identify the immediate sources and recipients of data outside the system;
- Show where data is held in the system.
- Form the basis of function definition and event identification

Mapping of the information infrastructure for a mode is equivalent to the DFM stage in system analysis, hence the relevance of the DFD technique. DFD consist of the following elements (Figure D:1):

- *Processes*, which represent the transformation or manipulation of data;
- *Data flows*, which are channels between other elements down which predefined sets of data may flow;
- *Data stores*, which represent data at rest;
- *External entities*; which are sources or recipients of data immediately outside the system boundary.

Data and the transformation of data can be tracked around a DFD but although a DFD does not show the sequence of processes nor decision points in the same way as a flowchart, it is a suitable method for the current application.

Figure D:1: Symbols in a Data Flow Diagram

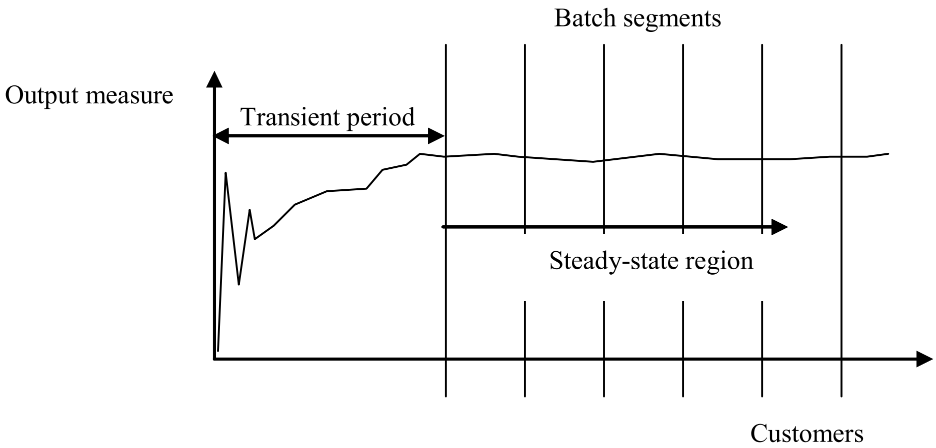


Appendix E
Simulation details

E.1 Sampling method

The VBTO system is analysed as a non-terminating system. The transient period from the start of the simulation to steady-state has been excluded. Too short a warm-up period will bias the findings. Due to running time the method of batch means has been used for collecting statistics. An incorrect batch length can bias the results due to autocorrelation effects (Law & Kelton 2000). The data collection method is sketched in Figure E:1.

Figure E:1 Simulation data collection method



E.1.1 Warm-up period

The task is to choose the length of warm-up such that bias from the transient period is avoided. Law & Kelton (2000) note that many methods have been proposed but they have not been found to perform well. A practical method is to plot simulation data and estimate the transient period by observation. For several pipeline lengths and variety combinations the rolling cumulative plots for one of the fulfilment mechanisms are shown below (Figure E:2 to Figure E:5). From observation it is apparent all simulations tend to a stable condition, and that the transient period varies with pipeline and variety.

Estimating the transient period from the cumulative plot would over-play its length. The plots of sequential and rolling batch both show how the behaviour of the VBTO system stabilises much earlier than shown in the cumulative graph (compare Figure E:6 and Figure E:7 to Figure E:5). The same is observed in comparing Figure E:2 to Figure E:8 and Figure E:9.

In the simulation studies a warm-up period of at least the length of the pipeline has been used (which is the case for Chapter 8). In each of Chapters 9 and 10 only one pipeline length and product variety ratio are used, and the respective warm-up periods are:

- Chapter 9 (pipeline 300, variety 625): warm-up 500
- Chapter 10 (pipeline 90, variety 256): warm-up 400

Figure E:2 Cumulative plot of customers fulfilled from the pipeline stock: pipeline 64, variety 32

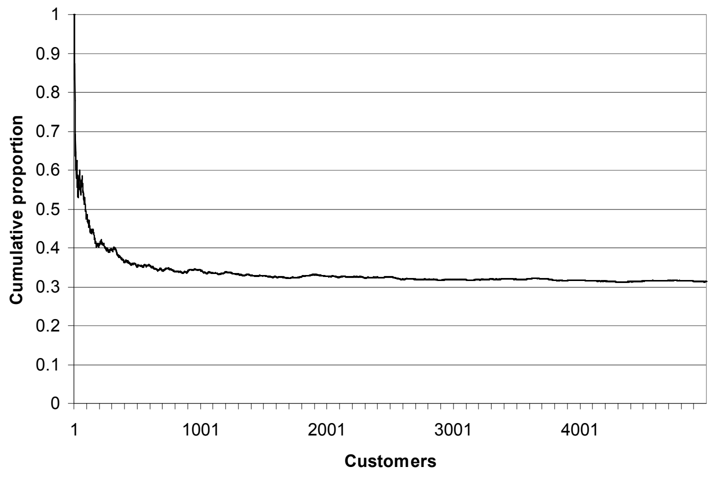


Figure E:3 Cumulative plot of customers fulfilled by stock: pipeline 90, variety 256

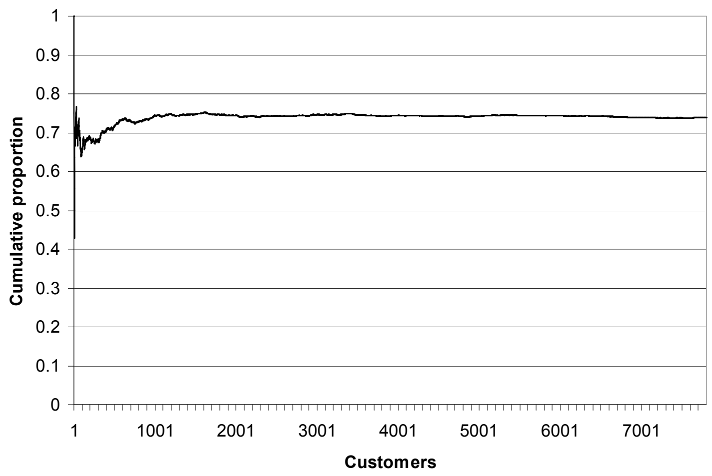


Figure E:4 Cumulative plot of customers fulfilled by BTO: pipeline 300, variety 625

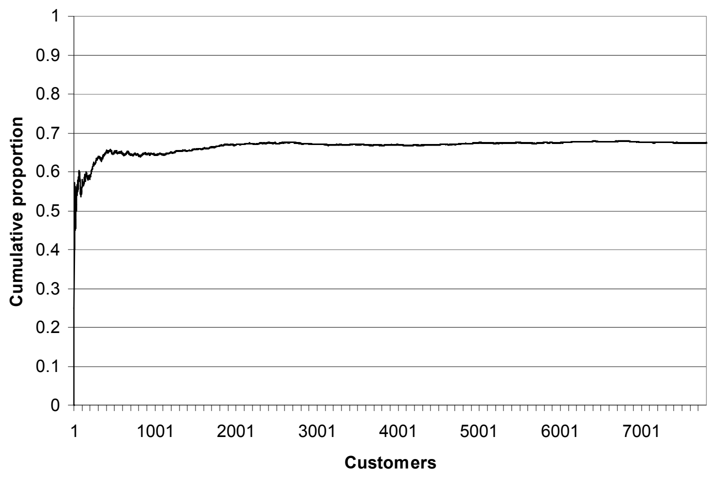


Figure E:5 Cumulative plot of customers fulfilled by stock: pipeline 2048, variety 2048

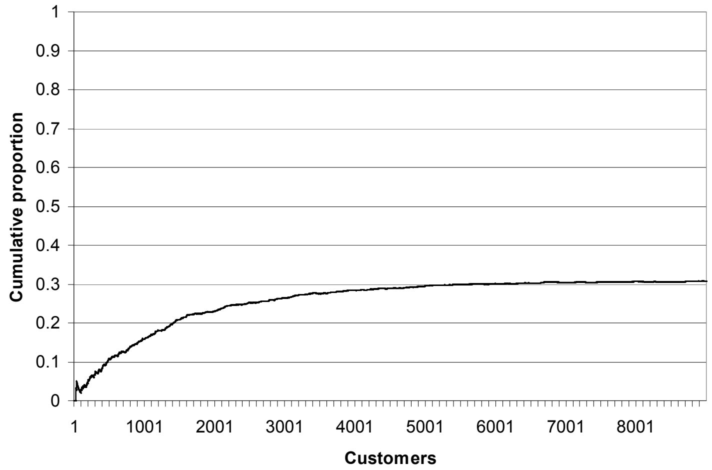


Figure E:6 Sequential batch average of customers fulfilled by stock: pipeline 2048, variety 2048, batch 25

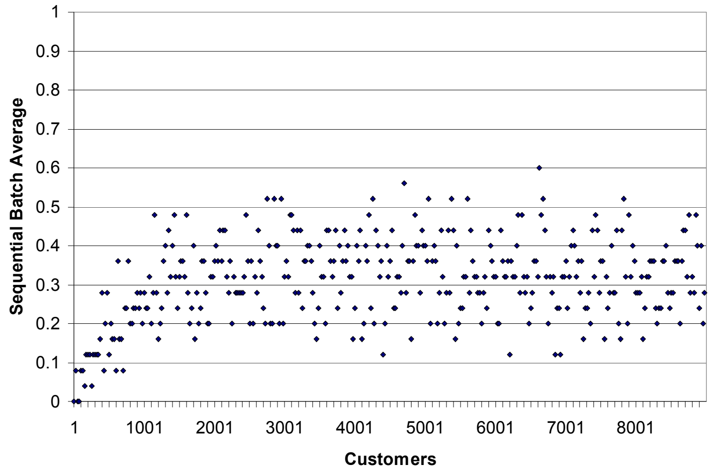


Figure E:7 Rolling batch average of customers fulfilled by stock: pipeline 2048, variety 2048, batch 25

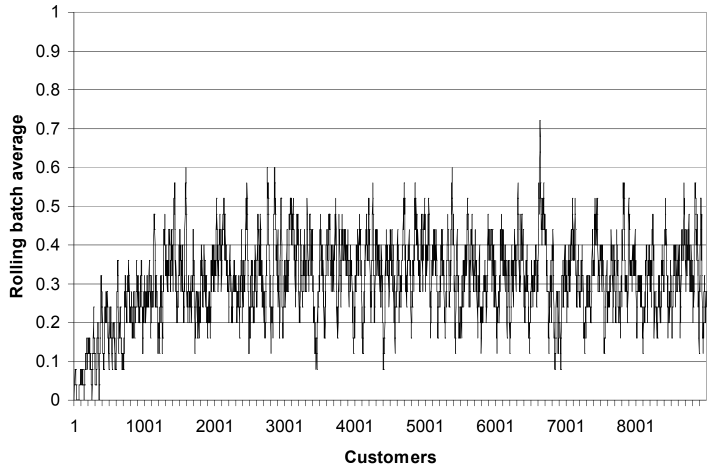


Figure E:8 Sequential batch average of customers fulfilled by stock: pipeline 64, variety 32, batch 25

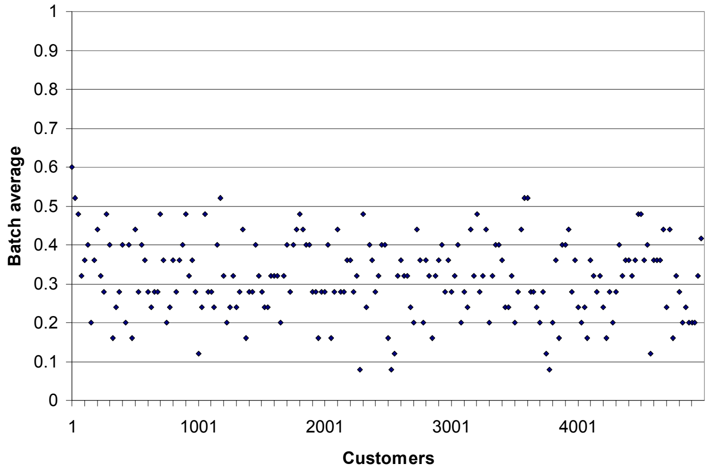
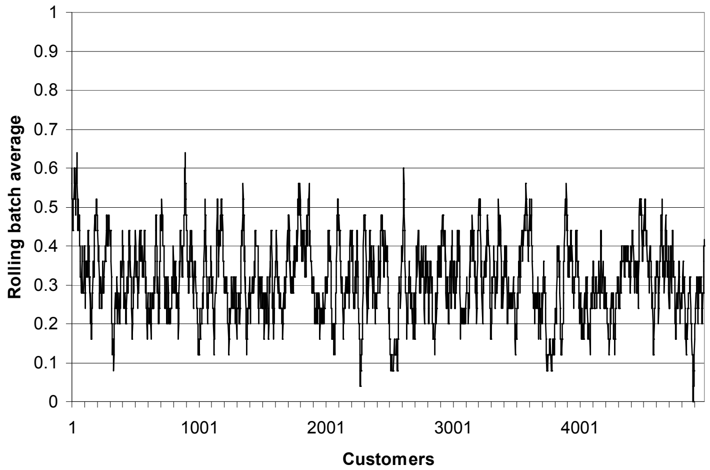


Figure E:9 Rolling batch average of customers fulfilled by stock: pipeline 64, variety 32, batch 25



E.1.2 Batch length

The batch length has been selected by first identifying the interval at which any two observations are not correlated. Correlograms for several pipeline and variety combinations are plotted below, from which is evident that correlation is negligible at a lag of no more than 100 or so (Figure E:10 to Figure E:13). The batch length has been set at higher figure. Throughout Chapter 8 in which different pipeline lengths are used appropriate batch lengths have been used. In Chapters 9 and 10 only one pipeline length and product variety ratio are used in each, and in these simulations a discarded *dead period* between each batch has also been used as a further precaution against autocorrelation effects. The batch lengths and dead periods are as follows:

- Chapter 9 (pipeline 300, variety 625): batch length 800, inter-batch dead period 200
- Chapter 10 (pipeline 90, variety 256): batch length 300, inter-batch dead period 50

Throughout the simulation studies 9 batches have been used.

Figure E:10 Correlogram for pipe fulfilment: pipeline 64, variety 32

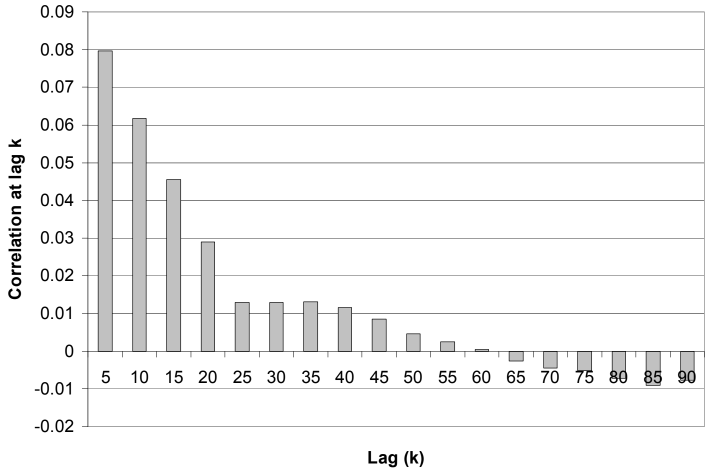


Figure E:11 Correlogram for BTO fulfilment: pipeline 90, variety 256

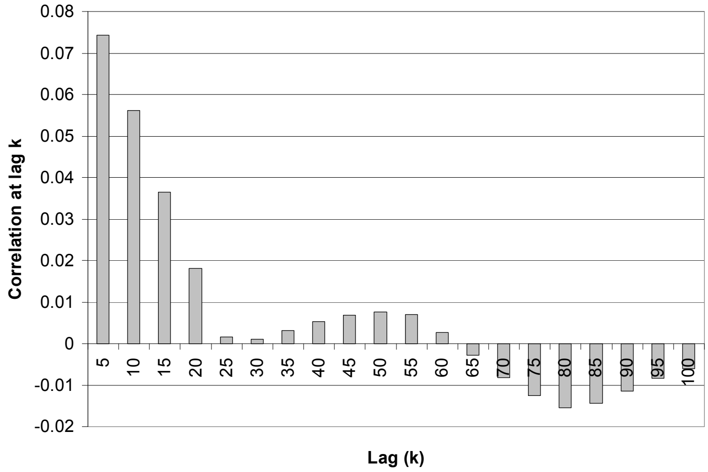


Figure E:12 Correlogram for BTO fulfilment: pipeline 300, variety 625

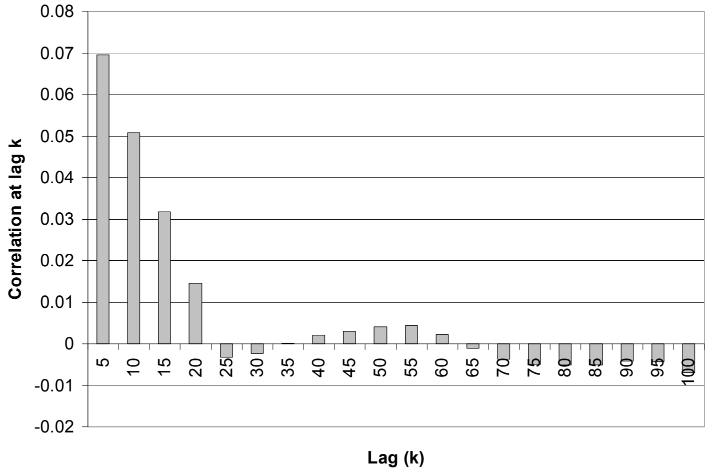
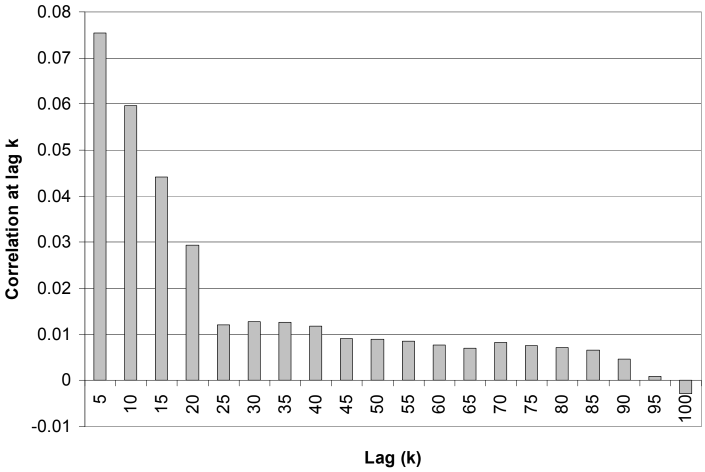


Figure E:13 Correlogram for stock fulfilment: pipeline 2048, variety 2048



Appendix F
Markov modelling support analysis

F.1 Verification of matching probabilities in stagnant conditions

An event tree model (Figure F:2) using equation [15-7] is compared to a simulation for a stagnant set of 3 products. When the product variety is 4 the likelihood of a match in an independent random search is 0.578. Using the data from the event tree model, the likelihood of the second search being successful if the first is unsuccessful is 0.528. The probability of a match declines with successive searches (Table F:1) and these calculations agree with the results from a simulation for which the probabilities up to the ninth customer have been generated Figure F:1.

Table F:1 Probability of a match in the search of a stagnant set of 3

Search	Probability of a match
First	0.578
Second	0.528
Third	0.485
Fourth	0.450
Fifth	0.419
Sixth	0.390

Figure F:1 Matching probability for a sequence of customers searching a stagnant set. Comparison of probabilities derived from an event tree model and simulation (product range 4, stagnant set 3)

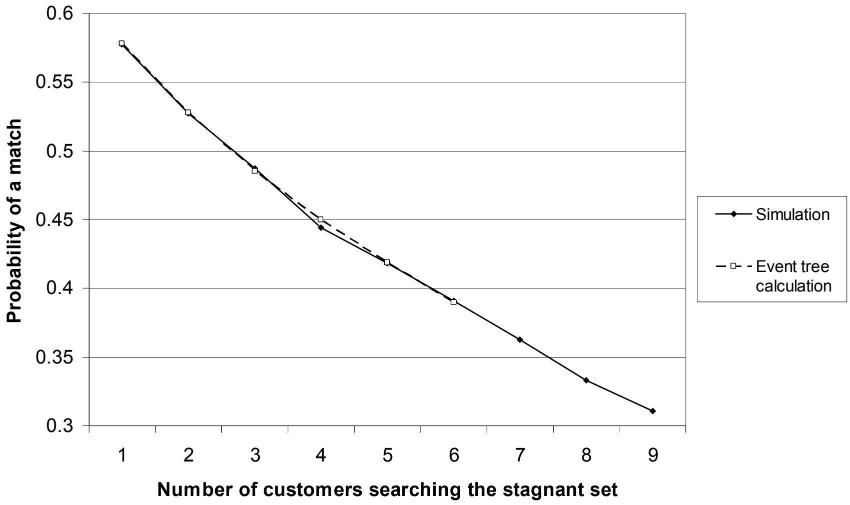
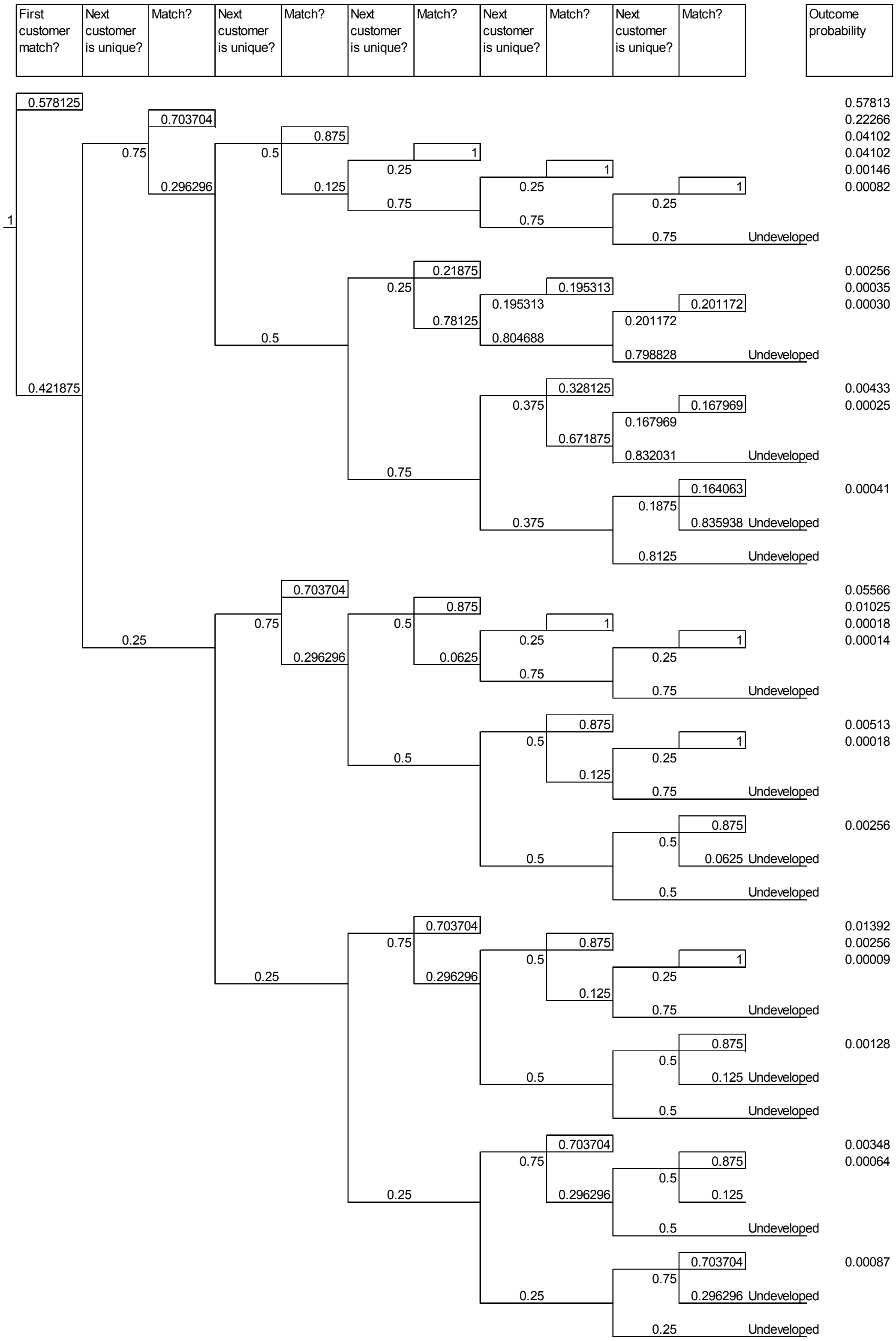


Figure F:2 Event tree model, developed up to the sixth search of a stagnant set (product range 4, stagnant set 3) Note: the upward branch is affirmative

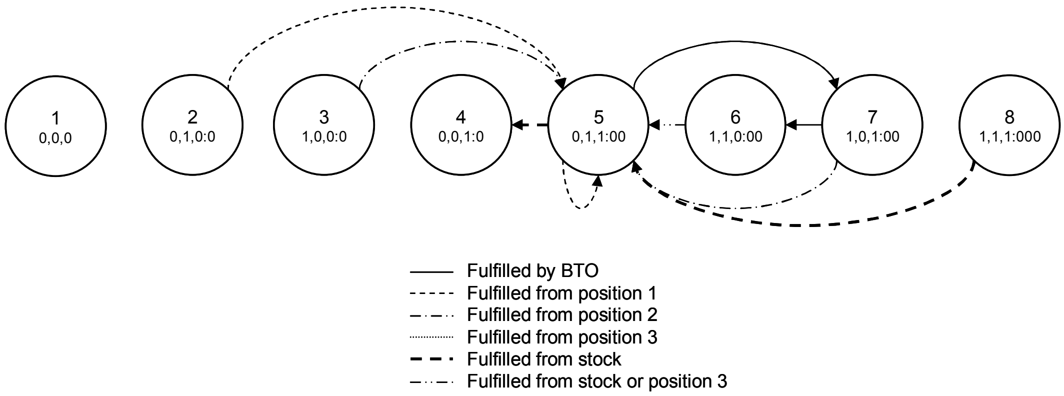


F.2 Dependency analysis

Table F:2 presents an analysis of the dependencies between a transition and the transitions that immediately precede it. A calculation is made of the transition probability of a transition given that it was preceded by a particular transition. This is then aggregated to give an estimate of the transition probability.

To explain further, consider the transitions into and out of state 5 (Figure F:3). There are three transitions out of state 5: to state 4, to state 7 and the transition that returns it to state 5. There are six transitions into state 5 and the probabilities of the three outward transitions do depend on which of these transitions occurred beforehand. For example, the outgoing transition 5\7 requires that the three available products are searched but no match is found. If transition 2\5 preceded it, then it is known that two of the available products have been searched immediately beforehand. Therefore, the calculation of this transition's probability (5\7) needs to take account of the fact that two of the three have been searched and the last has not. Figure F:6 is an event tree that takes account of this situation and gives a transition probability of 0.438 (outcome ref 10). If transition 8\5 occurred beforehand, the calculation is more involved since transition 8\5 has three versions. In transition 8\5 a customer is fulfilled by finding a match with one of three products in stock. The customer could have found a match with the first product examined, the second or the third. If transition 8\5 had been by the customer matching the first product examined, then the other two products would not have been searched. In the subsequent transition from 5\7 these two products can be considered to be fresh rather than stagnant hence the transition probability is taken from Figure F:4 (outcome ref 3). If the transition 8\5 had been by the customer matching the second product they had examined, then in the subsequent transition it is necessary to take account of one having been searched and the other not. The probability is from Figure F:5 (outcome 11).

Figure F:3: All Transitions into and out of state 5



For some transition pairs it is necessary that the customer be seeking a different specification from the preceding customer. Examples of this are when transition 5\4 is preceded by any of: 2\5, 3\5, 5\5, 6\5 (but not if this involved the preceding customer finding a match with the first item searched), 7\5, and 8\5 (but not if this involved the preceding customer finding a match with the first item searched). This is also taken into account in the analysis, with a column in Table F:2 identifying whether the customer must be unique.

Table F:2: Transition analysis table

Transition			Preceding transition							
No.	How the customer is fulfilled	Missed	No.	How the customer is fulfilled	Missed (note: the position the product will be in when next searched is indicated in brackets)	How many are searched twice?	Customer must be different?	Outcome reference (in Figure F:4 to Figure F:7)	Transition probability	Average
1\1	3		1\1	3				1	0.250	0.250
			4\1	S				1	0.250	
1\2	1	3,2	1\1	3				2	0.141	0.141
			4\1	S				2	0.141	
1\3	BTO	3,2,1	1\1	3				3	0.422	0.422
			4\1	S				3	0.422	
1\4	2	3	1\1	3				4	0.188	0.188
			4\1	S				4	0.188	
2\4	S		1\2	1	3(S), 2(3)	1	Yes	5	0.250	0.250
			3\2	S				1	0.250	
			3\2	3	S	1	Yes	5	0.250	
			4\2	1	S, 2(3)	1	Yes	5	0.250	
			7\2	S1				1	0.250	
			7\2	S2	S1	1	Yes	5	0.250	
2\4	3	S	1\2	1	3(S), 2(3)	2	Yes	6	0.167	0.181
			3\2	S				4	0.188	

Transition			Preceding transition							
No.	How the customer is fulfilled	Missed	No.	How the customer is fulfilled	Missed (note: the position the product will be in when next searched is indicated in brackets)	How many are searched twice?	Customer must be different?	Outcome reference (in Figure F:4 to Figure F:7)	Transition probability	Average
			3\2	3	S	1		7	0.188	
			4\2	1	S, 2(3)	2	Yes	6	0.167	
			7\2	S1				4	0.188	
			7\2	S2	S1	1		7	0.188	
2\5	1	S,3	1\2	1	3(S), 2(3)	2		8	0.146	0.142
			3\2	S				2	0.141	
			3\2	3	S	1		9	0.141	
			4\2	1	S, 2(3)	2		8	0.146	
			7\2	S1				2	0.141	
			7\2	S2	S1	1		9	0.141	
2\7	BTO	S,3,1	1\2	1	3(S), 2(3)	2		10	0.438	0.427
			3\2	S				3	0.422	
			3\2	3	S	1		11	0.422	
			4\2	1	S, 2(3)	2		10	0.438	
			7\2	S1				3	0.422	
			7\2	S2	S1	1		11	0.422	
3\2	S		1\3	BTO	3(S),2(3),1(2)	1	Yes	5	0.250	0.250
			4\3	BTO	S,2(3),1(2)	1	Yes	5	0.250	

Transition			Preceding transition							
No.	How the customer is fulfilled	Missed	No.	How the customer is fulfilled	Missed (note: the position the product will be in when next searched is indicated in brackets)	How many are searched twice?	Customer must be different?	Outcome reference (in Figure F:4 to Figure F:7)	Transition probability	Average
3\2	3	S	1\3	BTO	3(S),2(3),1(2)	2	Yes	6	0.167	0.167
			4\3	BTO	S,2(3),1(2)	2	Yes	6	0.167	
3\5	2	S,3	1\3	BTO	3(S),2(3),1(2)	3	Yes	12	0.111	0.111
			4\3	BTO	S,2(3),1(2)	3	Yes	12	0.111	
3\6	BTO	S,3,2	1\3	BTO	3(S),2(3),1(2)	3		13	0.472	0.472
			4\3	BTO	S,2(3),1(2)	3		13	0.472	
4\1	S		1\4	2	3(S)	1	Yes	5	0.250	0.250
			2\4	S				1	0.250	
			4\4	2	S	1	Yes	5	0.250	
			5\4	S1				1	0.250	
			5\4	S2	S1	1	Yes	5	0.250	
4\2	1	S,2	1\4	2	3(S)	1		9	0.141	0.141
			2\4	S				2	0.141	
			4\4	2	S	1		9	0.141	
			5\4	S1				2	0.141	
			5\4	S2	S1	1		9	0.141	
4\3	BTO	S,2,1	1\4	2	3(S)	1		11	0.422	0.422
			2\4	S				3	0.422	

Transition			Preceding transition							
No.	How the customer is fulfilled	Missed	No.	How the customer is fulfilled	Missed (note: the position the product will be in when next searched is indicated in brackets)	How many are searched twice?	Customer must be different?	Outcome reference (in Figure F:4 to Figure F:7)	Transition probability	Average
			4\4	2	S	1		11	0.422	
			5\4	S1				3	0.422	
			5\4	S2	S1	1		11	0.422	
4\4	2	S	1\4	2	3(S)	1		7	0.188	0.188
			2\4	S				4	0.188	
			4\4	2	S	1		7	0.188	
			5\4	S1				4	0.188	
			5\4	S2	S1	1		7	0.188	
5\4	S1		2\5	1	S(S1),3(S2)	1	Yes	5	0.250	0.250
			3\5	2	S(S1),3(S2)	1	Yes	5	0.250	
			5\5	1	S1,S2	1	Yes	5	0.250	
			6\5	S1				1	0.250	
			6\5	S2	S1	1	Yes	5	0.250	
			6\5	3	S1,S2	1	Yes	5	0.250	
			7\5	2	S1,S2	1	Yes	5	0.250	
			8\5	S1				1	0.250	
			8\5	S2	S1	1	Yes	5	0.250	
			8\5	S3	S1,S2	1	Yes	5	0.250	

Transition			Preceding transition							
No.	How the customer is fulfilled	Missed	No.	How the customer is fulfilled	Missed (note: the position the product will be in when next searched is indicated in brackets)	How many are searched twice?	Customer must be different?	Outcome reference (in Figure F:4 to Figure F:7)	Transition probability	Average
5\4	S2	S1	2\5	1	S(S1),3(S2)	2	Yes	6	0.167	0.175
			3\5	2	S(S1),3(S2)	2	Yes	6	0.167	
			5\5	1	S1,S2	2	Yes	6	0.167	
			6\5	S1				4	0.188	
			6\5	S2	S1	1		7	0.188	
			6\5	3	S1,S2	2	Yes	6	0.167	
			7\5	2	S1,S2	2	Yes	6	0.167	
			8\5	S1				4	0.188	
			8\5	S2	S1	1		7	0.188	
			8\5	S3	S1,S2	2	Yes	6	0.167	
5\5	1	S1,S2	2\5	1	S(S1),3(S2)	2		8	0.146	0.144
			3\5	2	S(S1),3(S2)	2		8	0.146	
			5\5	1	S1,S2	2		8	0.146	
			6\5	S1				2	0.141	
			6\5	S2	S1	1		9	0.141	
			6\5	3	S1,S2	2		8	0.146	
			7\5	2	S1,S2	2		8	0.146	
			8\5	S1				2	0.141	

Transition No.	Transition: How the customer is fulfilled	Transition: Missed	Preceding transition No.	Preceding transition: How the customer is fulfilled	Preceding transition: Missed (note: the position the product will be in when next searched is indicated in brackets)	How many are searched twice?	Customer must be different?	Outcome reference (in Figure F:4 to Figure F:7)	Transition probability	Average
			8\5	S2	S1	1		9	0.141	
			8\5	S3	S1,S2	2		8	0.146	
5\7	BTO	S1,S2,1	2\5	1	S(S1),3(S2)	2		10	0.438	0.431
			3\5	2	S(S1),3(S2)	2		10	0.438	
			5\5	1	S1,S2	2		10	0.438	
			6\5	S1				3	0.422	
			6\5	S2	S1	1		11	0.422	
			6\5	3	S1,S2	2		10	0.438	
			7\5	2	S1,S2	2		10	0.438	
			8\5	S1				3	0.422	
			8\5	S2	S1	1		11	0.422	
			8\5	S3	S1,S2	2		10	0.438	
6\5	3	S1,S2	3\6	BTO	S(S1),3(S2),2(3)	3	Yes	12	0.111	0.111
			7\6	BTO	S1,S2,2(3)	3	Yes	12	0.111	
6\5	S2	S1	3\6	BTO	S(S1),3(S2),2(3)	2	Yes	6	0.167	0.167
			7\6	BTO	S1,S2,2(3)	2	Yes	6	0.167	
6\5	S1		3\6	BTO	S(S1),3(S2),2(3)	1	Yes	5	0.250	0.250
			7\6	BTO	S1,S2,2(3)	1	Yes	5	0.250	

Transition			Preceding transition							
No.	How the customer is fulfilled	Missed	No.	How the customer is fulfilled	Missed (note: the position the product will be in when next searched is indicated in brackets)	How many are searched twice?	Customer must be different?	Outcome reference (in Figure F:4 to Figure F:7)	Transition probability	Average
6\8	BTO	S1,S2,3	3\6	BTO	S(S1),3(S2),2(3)	3		13	0.472	0.472
			7\6	BTO	S1,S2,2(3)	3		13	0.472	
7\2	S1		2\7	BTO	S(S1),3(S2),1(2)	1	Yes	5	0.250	0.250
			5\7	BTO	S1,S2,1(2)	1	Yes	5	0.250	
7\2	S2	S1	2\7	BTO	S(S1),3(S2),1(2)	2	Yes	6	0.167	0.167
			5\7	BTO	S1,S2,1(2)	2	Yes	6	0.167	
7\5	2	S1,S2	2\7	BTO	S(S1),3(S2),1(2)	3	Yes	12	0.111	0.111
			5\7	BTO	S1,S2,1(2)	3	Yes	12	0.111	
7\6	BTO	S1,S2,2	2\7	BTO	S(S1),3(S2),1(2)	3		13	0.472	0.472
			5\7	BTO	S1,S2,1(2)	3		13	0.472	
8\5	S1		6\8	BTO	S1,S2,3(S3)	1	Yes	5	0.250	0.250
			8\8	BTO	S1,S2,S3	1	Yes	5	0.250	
8\5	S2	S1	6\8	BTO	S1,S2,3(S3)	2	Yes	6	0.167	0.167
			8\8	BTO	S1,S2,S3	2	Yes	6	0.167	
8\5	S3	S1,S2	6\8	BTO	S1,S2,3(S3)	3	Yes	12	0.111	0.111
			8\8	BTO	S1,S2,S3	3	Yes	12	0.111	
8\8	BTO	S1,S2,S3	6\8	BTO	S1,S2,3(S3)	3		13	0.472	0.472

Transition			Preceding transition							
No.	How the customer is fulfilled	Missed	No.	How the customer is fulfilled	Missed (note: the position the product will be in when next searched is indicated in brackets)	How many are searched twice?	Customer must be different?	Outcome reference (in Figure F:4 to Figure F:7)	Transition probability	Average
			8\8	BTO	S1,S2,S3	3		13	0.472	

S = product in stock; S1 = First to be searched of the products in stock; S2 = Second to be searched of the products in stock; S3 = Third to be searched of the products in stock

F.2.1 Event trees for Transition probability calculations

Four event trees are constructed to calculate the conditional transition probabilities. The four scenarios requiring separate calculations are:

- No dependence between a pair of transitions, i.e. the set of searched products is treated as a refreshed set.
- Dependence condition 1: one of the products was searched in the preceding transition.
- Dependence condition 2: two of the products were searched in the preceding transition.
- Dependence condition 3: three of the products were searched in the preceding transition.

The four event trees have the same structure. The first branch asks whether the customer is different from the previous customer. This is calculated as n-1/n (equation [2]). The next branch asks whether there is a match with the first product searched. If the product has not been searched by the preceding customer the branch probability is 1/n whether or not the customer is different from the preceding customer. If this product has been searched before, the branch probability is 1/(n-1) if the customer is different, or 0 (zero) if the customer is the same as the preceding customer. The branch probabilities are summarised in Table F:3.

The outcomes in the event trees are cross-referenced to Table F:2

F.2.2 Comment on the dependency analysis

The analysis takes account only of the immediately preceding transitions and has, therefore, not quantified the effect of earlier transitions. A second shortcoming of this analysis lies in the averaging of the preceding probabilities to give an aggregate transition probability. There may be scope to improve this by weighting each of the preceding transitions by the state probabilities. This would require an iterative process: firstly the transition probabilities would be calculated assuming all preceding states had equal probability, secondly the steady-state probabilities would be determined, and then the transition probabilities would be readjusted to reflect the revised state probabilities, and so on.

Table F:3: Branch probabilities

Branch	Equation	Value when variety (n) is 4
Customer is different	n-1/n	0.75
Product is a match in an independent search	1/n	0.25
Product is a match in a dependent search (and the customer is different)	1/(n-1)	0.33

Figure F:4: Event tree for independent transition (pipe length 3, variety 4)

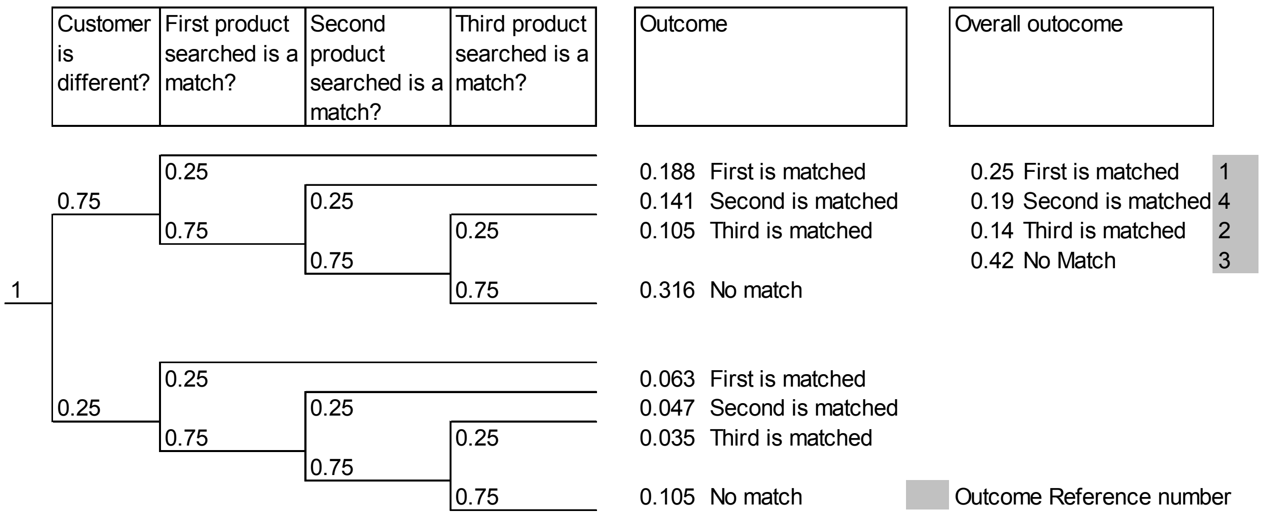


Figure F:5: Event tree for a transition in which the first search is dependent (pipe length 3, variety 4)

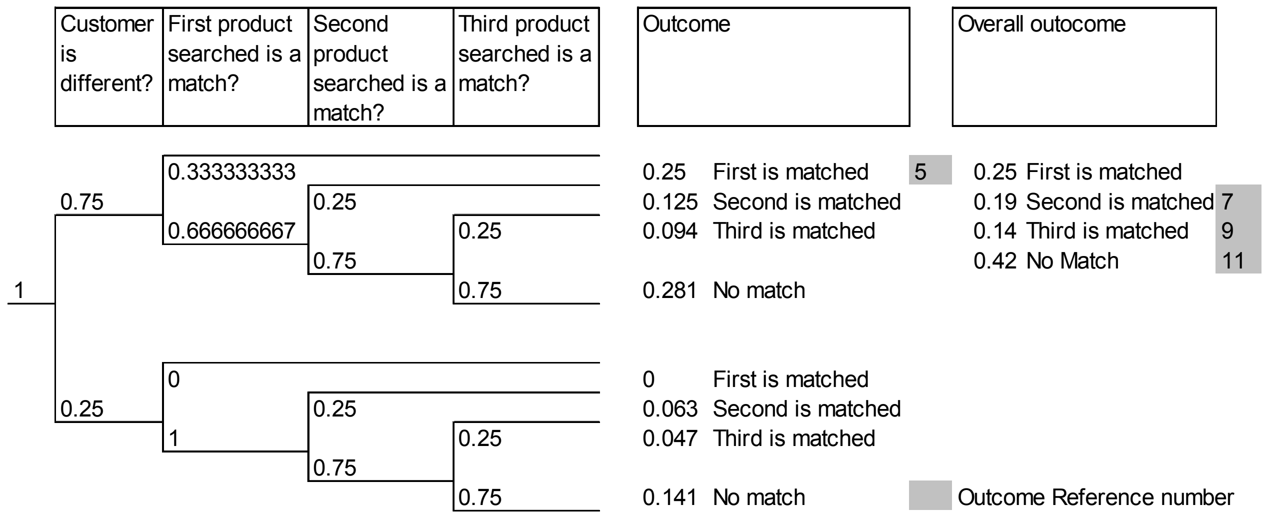


Figure F:6: Event tree for a transition in which first and second searches are dependent (pipe length 3, variety 4)

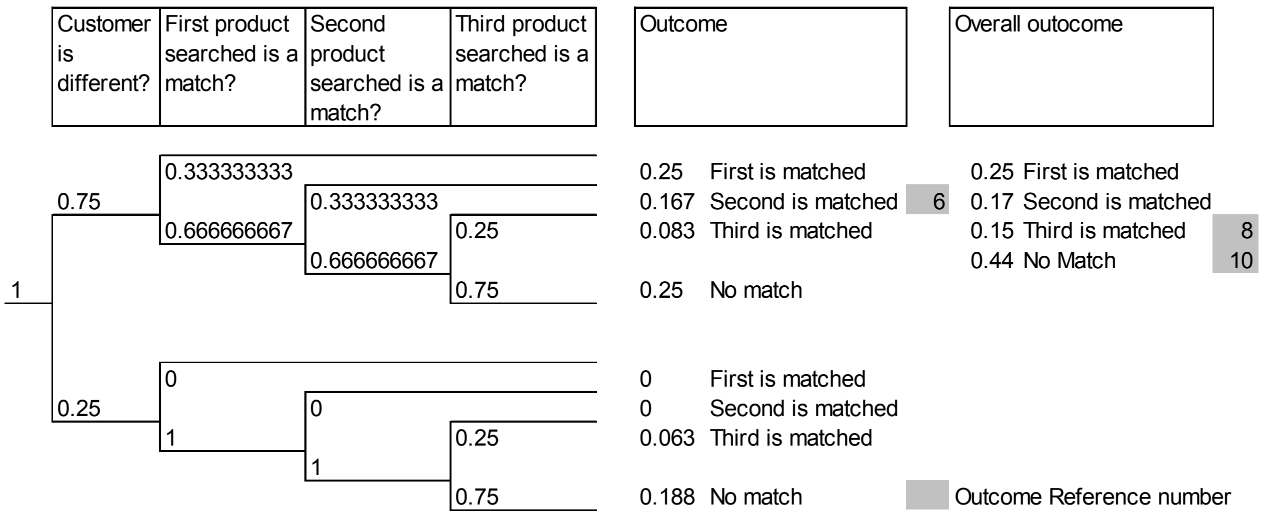


Figure F:7: Event tree for a transition in which first, second and third searches are dependent (pipe length 3, variety 4)