**CRANFIELD UNIVERSITY**

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# THE APPLICATION OF FORM POSTPONEMENT IN MANUFACTURING

**SCHOOL OF MANAGEMENT**

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# The Application of Form Postponement in Manufacturing

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## Abstract

Postponement is widely recognised as an approach that can lead to superior supply chains, and its application is widely observed as a growing trend in manufacturing. Form postponement (FPp) involves the delay of final manufacturing until a customer order is received and is commonly regarded as an approach to mass customisation. However, while much is written in the literature on the benefits and strategic impact of FPp, little is still known about its application. Thus this research project aims to address how FPp is applied in terms of the operational implications within the manufacturing facility. Here the 'postponed' manufacturing processes are performed in the factory where the preceding processes are carried out.

An in-depth case study research design was developed and involved case studies at three manufacturing facilities, which provided diverse contexts in which to study FPp applications. Each case study incorporated multiple units of analysis which were based around product groups subject to different inventory management policies – FPp, make to order (MTO) and make to stock (MTS). The same research design was used in each study and involved both qualitative and quantitative evidence. Qualitative evidence was gathered via structured interviews and included the operational changes required to apply FPp in a previously MTO and MTS environment. Eleven quantitative variables, providing a broad based measurement instrument, were compared across the three units of analysis to test the hypotheses. This combination of qualitative and quantitative evidence in the case studies helped to triangulate the research findings. Comparison between the three case studies provided further conclusions regarding operational implications that were context specific and those which were not.

The research concludes that the manufacturing planning system presents a major obstacle to the application of FPp in a MTO and MTS environment. In spite of this, and even when the FPp application is flawed, the benefits of FPp still justify its application. The research also contributes two frameworks: one which determines when FPp is a viable alternative to MTO or MTS; and another that illustrates the major operational implications of applying FPp to a product exhibiting component swapping modularity.

## ACKNOWLEDGEMENTS

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*Heather Skipworth*
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*September, 2003.*

# Table of Contents

# Table of Figures

# Table of Tables

# CHAPTER ONE

# 1 Introduction to the Research

## 1.1 RESEARCH RATIONALE

The dynamic and intensely competitive marketplace of today coupled with the increased pace of technological change, has led to shortening product life cycles and a proliferation of product variety (Kotha 1995). Moreover a greater degree of responsiveness, in terms of short, reliable delivery lead-times is demanded by a market where time is increasingly seen as a key driver (Battacharya 1995). Despite the benefits to consumers, this phenomenon makes it more difficult for manufacturing operations either to predict product sales or to plan production to support responsive supply (Fisher 1997).

Mass customisation is a manufacturing response to this phenomenon. It was first introduced by Davis (1987) to describe a trend towards the production and distribution of individually customised goods and services for a mass market. More recently, mass customisation has been described as 'providing numerous customer chosen variations on every order with little lead-time or cost penalty' (Ahlstrom and Westbrook 1999). The implied challenge for manufacturers is how to deal with the high demand uncertainty, resulting from the provision of many variants, whilst ensuring low operational costs are maintained, within short, reliable lead-times.

The traditional response to high demand uncertainty in a make-to-stock (MTS) environment is to buffer against the uncertainties by increasing safety stocks (for example Metters 1993, Newman et al. 1993, Scott and Westbrook 1991). However, in the case of customised products, it is rarely economically viable to maintain the safety stock levels required to avoid stock-outs. Thus inaccurate sales forecasts are increasingly leading to costly discrepancies between finished stocks and demand. It is argued that - whatever the degree of customisation - the product can only be made or at least finished to order (Amaro et al. 1999, Bennett and Forrester 1994).

Form postponement has been proposed as one of the more effective approaches to mass customisation (for example Amaro et al. 1999, Bowersox and Closs 1996, Pine 1993, van Hoek 1998, van Hoek et al. 1996 and 1998, Zinn and Bowersox 1988). Postponement, in general terms, seeks to delay final formulation, or movement, of a product until after customer orders are received (Zinn and Bowersox, 1988). In contrast the MTS approach aims to conduct final manufacturing, and most inventory movement, in *anticipation* of customer orders - normally to sales forecasts. Thus postponement reduces the risk of improper manufacture or inventory distribution associated with MTS. At the other extreme, make-to-order (MTO) is where the manufacturer takes no action until receipt of a customer order. Therefore the entire production process is *order driven*. In practice this is rarely practicable and many raw materials are purchased in anticipation of customer orders. Postponement compared to MTO improves responsiveness and still enables a high level of customisation. It should be noted that here, and throughout this thesis, responsiveness is the ability to respond to fluctuating customer demand in terms of delivery speed or order lead-time. This is an element of responsiveness as described by the framework developed by Kritchanchai and MacCarthy (1999). Not the Matson and McFarlane (1999) definition of production responsiveness as the ability of a production system to achieve its goals in the presence of disturbances.

Postponement is thus widely recognised as an approach that can lead to superior logistics systems or supply chains (for example Cooper 1993, Jones and Riley 1985, Scott and Westbrook 1991, Shapiro and Heskett 1985). Further, the application of postponement has been observed as a growing trend in manufacturing and distribution by various surveys (CLM 1995, Ahlstrom and Westbrook 1999) and prominent researchers (Christopher 1998, Lampel and Mintzberg 1996).

Yang and Burns (2003) point out that ‘postponement fosters a new way of thinking about product design, process design and supply chain management. For example it encourages companies to decide which components will be modular, standard and customisable….where and which inventories are justified, and what activities are based on forecast (or order)’. However Yang and Burns (2003) further comment that 'although much is written in the literature on the benefits of postponement… little is still known about the implementation of postponement'.

Before considering the research project it is necessary first to explore the concept of form postponement to enable an appreciation of the operational implications in applying it.

## 1.2 THE FORM POSTPONEMENT CONCEPT

This section introduces the concept of form postponement by considering *form* (or manufacturing) postponement and *logistical* (or time) postponement - the two main types of postponement. A definition of form postponement is provided and the dichotomy in manufacturing arising from the application of form postponement is discussed.

### *1.2.1 Logistical or Form Postponement*

The key distinction between logistical and form postponement is the extent to which the manufacturing process is driven by customer orders rather than by forecasts. In turn this hinges on the location of the Customer Order Decoupling Point (CODP) as illustrated in Figure 1.1. The CODP is the point in the chain of value adding processes where a product is linked to a *specific customer order*, therefore downstream from this point production is order-driven and upstream it is forecast-driven (Browne et al. 1996, Hoekstra and Romme 1992, Van Veen 1992). This usually means that the CODP coincides with the final speculative stock point.

In the case of form postponement the CODP is at the *semi-finished product* stage, where the product or component modules are in a *generic* form. The final manufacturing which *differentiates* the product is performed to specific customer orders (Zinn and Bowersox 1988, Bowersox and Closs 1996).

Bowersox and Closs (1996) offer the following definition of logistical postponement:

> *'The basic notion of logistical or time postponement is to maintain a full line anticipatory inventory at one or a few strategic locations. Forward deployment of inventory is postponed until customer orders are received.'*

The CODP, therefore, is positioned at the finished product stage (Bowersox and Closs 1996, van Hoek et al. 1996 and 1998).

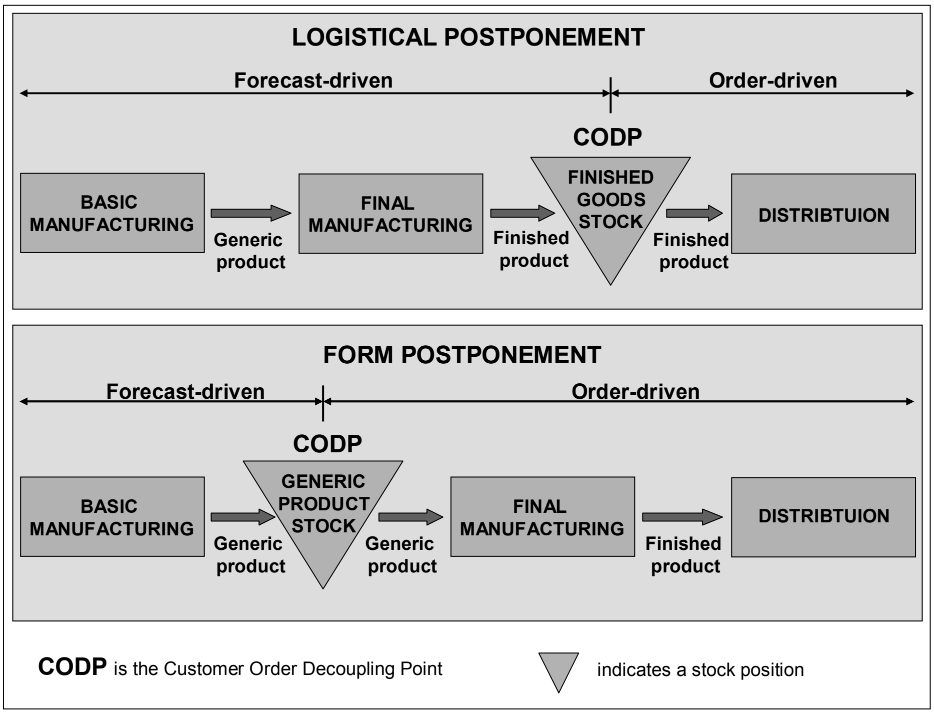



**Figure 1.1: A schematic illustrating the location of the Customer Order Decoupling Point for form and logistical postponement**

The benefits of logistical postponement are widely professed in the logistics literature. For instance Bowersox and Closs (1996) claim it improves customer service and lowers overall inventory investment, whilst preserving mass manufacturing economies of scale in their entirety. Van Hoek (1998b) suggests that the centralisation of inventories in European Distribution Centres (that service a number of countries from one location) is a practical example of logistical postponement. However many applications of logistical postponement involve service supply parts, where critical and high cost parts are maintained in a central inventory to ensure availability to all potential users (Bowersox and Closs 1996). When demand for a part occurs shipments are made directly to the service facility using fast, reliable transportation.

Volvo GM Heavy Truck Corporation applied logistical postponement to the supply of commercial truck parts for emergency roadside repairs in the United States (Narus and Anderson 1996). The initiative was prompted by the discovery that inventories at the dealers were exceptionally high but the parts actually needed were rarely in stock. Volvo set up a national warehouse stocking the full line of truck parts and used FedEx Logistics to ship parts within 24 hours to the roadside repair site. This had the effect of both dramatically reducing parts inventory and improving service.

Logistical postponement is basically confined to the design of distribution networks. New and Skipworth (2000) conclude that it is concerned with 'the issue of where to hold finished stock in a distribution system in order to minimise stock holding but maintain a high level of customer responsiveness. This has been one of the classic problems of inventory theory for most of the last century and the solution involves balancing lead-time response, inventory location and transportation costs'. Logistical postponement is outside the scope of this research project which is principally concerned with the postponement of manufacturing transformation processes. These by definition involve the use of resources to change the state or condition of materials to produce goods (Slack et al. 1998). Thus this research project focuses exclusively on form postponement. The abbreviation FPp will be used for form postponement from this point on.

FPp enables the supply of a broad product line 'without the risks associated with building large finished inventories in anticipation of uncertain demand for specific items' (New and Skipworth 2000). It also partly preserves the mass manufacturing economies of scale arising from the MTS approach. This is illustrated by a well known example of FPp, which was applied in the Benetton clothing factory in Italy (Harvard Business School 1985, Dapiran 1992). In response to highly volatile demand for the different coloured jumpers Benetton postponed the dying process. The result was that the jumpers were manufactured in high volume from bleached yarn thus creating high manufacturing economies of scale, and only dyed upon the receipt of customer orders based on *actual jumper sales*. Consequently finished jumper inventory levels and the associated carrying costs, both at the factory and at the retailers, were radically reduced.

### *1.2.2 Defining Form Postponement*

There are many FPp examples in the logistics and operations literature illustrating its benefits, but crucial to this research is a precise and clear understanding of what FPp is.

At present the literature provides no consensus on such a definition of FPp. Instead there are a host of definitions expounding different ideas to varying levels of detail ( for example Zinn and Bowersox 1988, Lee and Billington 1994, Van Hoek 1998a and 1998c, Van Hoek et al. 1996 and 1998). The following working definition was developed from a review of existing FPp definitions (detailed in section 2.1) and was used for this research:

> *'**FPp** is the delay, until customer orders are received, of the final part of the transformation processes, through which the number of different product items proliferates and for which only a short time period is available. The postponed transformation processes may be manufacturing processes, assembly processes, configuration processes, packaging, or labelling processes.'*

It broadens the Zinn and Bowersox (1988) definition, commonly used in logistics literature, by *not* stipulating the geographical location of the postponed process. It acknowledges that the postponed process may take place not only at a warehouse but at a factory (as in 'bundled manufacturing' defined by Cooper 1993) or even at the retailers, and these locations may be near to or remote from the customers. The diversity suggested by this definition is evident in practice. For example Benetton dyed their jumpers in their main factory in Italy (Harvard Business School 1985) and Xerox configured their office digital products to order at their Gloucester plant (Christopher 1998). Caterpillar attached options such as lifts and forks to their forklift trucks to customer order in a US warehouse. Some paint retailers stock the generic paint and a variety of pigments mixing them to specific customer orders (Feitzinger and Lee 1997).

Logistics literature has naturally focussed on FPp applications where variety is added in the distribution chain. These tend to involve the postponement of relatively simple activities that are not operationally challenging in comparison with manufacturing operations. For example the postponed processes conducted in the warehouses by Motorola consists of programming the frequencies into the radios and labelling them accordingly (Andel 1997). It can be argued that when variety is added in the factory it is likely to involve the postponement of substantially more complex processes and the operational implications are more significant and difficult to manage. For example the postponed processes conducted in the Sony Manufacturing (UK) factory at Bridgend involved fitting PCBs and other components to the ‘Eurochassis’ (common to all products) which then underwent final assembly (Ferguson 1989).

| | **Logistics** | |
|---|---|---|
| | **Speculation** *Decentralised Inventories* | **Postponement** *Centralised inventories and direct distribution* |
| **Manufacturing** **Speculation** *Make –to-stock (MTS)* | **Full Speculation** | **Logistical Postponement** |
| *Form Postponement (FPp)* | **Distribution Form Postponement** | **Unicentric Form Postponement** |
| *Engineer/Make -to-order (ETO/MTO)* **Postponement** | **N/a** | **Full Postponement** |

**Figure 1.2: A matrix of generic postponement-speculation strategies (adapted from Pagh and Cooper 1998)**

This research project was therefore confined to FPp applications where the postponed process was performed in the same location as the generic processes – adding variety at the point of manufacture rather than in the distribution chain (‘bundled manufacturing’ according to Cooper 1993). Pagh and Cooper (1998) present a two by two matrix of generic postponement-speculation strategies (see Figure 1.2 for an adapted version). The dimensions are the degree of postponement-speculation in logistics and manufacturing. Logistics can range from a speculative strategy where inventories are speculatively distributed, and therefore decentralised, to a postponement strategy where distribution is postponed, and therefore inventories are centralised. Manufacturing can range from a speculative strategy characterised by MTS, to a FPp strategy. Pagh and Cooper (1998) term this ‘MTO’. This cannot be so, because part of the manufacturing is still conducted speculatively. Therefore this strategy is more accurately referred to as FPp (as labelled in Figure 1.2). Similarly Pagh and Cooper (1998) term the fourth quadrant strategy where both logistics and manufacturing is postponed as ‘full postponement'. It can be argued that 'full postponement' would be ETO or MTO (depending upon the type of product) where all activities are postponed, therefore another row has been added to the matrix to represent this.

The term 'unicentric FPp' is given to applications where the postponed process is performed in the same location as the generic processes (normally the factory) – adding variety at the point of manufacture rather than in the distribution chain. Alternatively the term 'distribution FPp' is given where the postponed process takes place in the distribution chain. This research project is confined to 'unicentric FPp' highlighted by the shaded box in Figure 1.2.

### *1.2.3 Dichotomy in manufacturing*

Meyer et al. (1989) report that one of the most striking results from their 1986 survey of large manufacturers in the three industrialised regions of the world, was the efforts made by the more advanced manufacturers to overcome the trade-off between flexibility and cost efficiency. It is this trade-off that FPp overcomes through the division of processing into two distinct stages (Starr 1965).

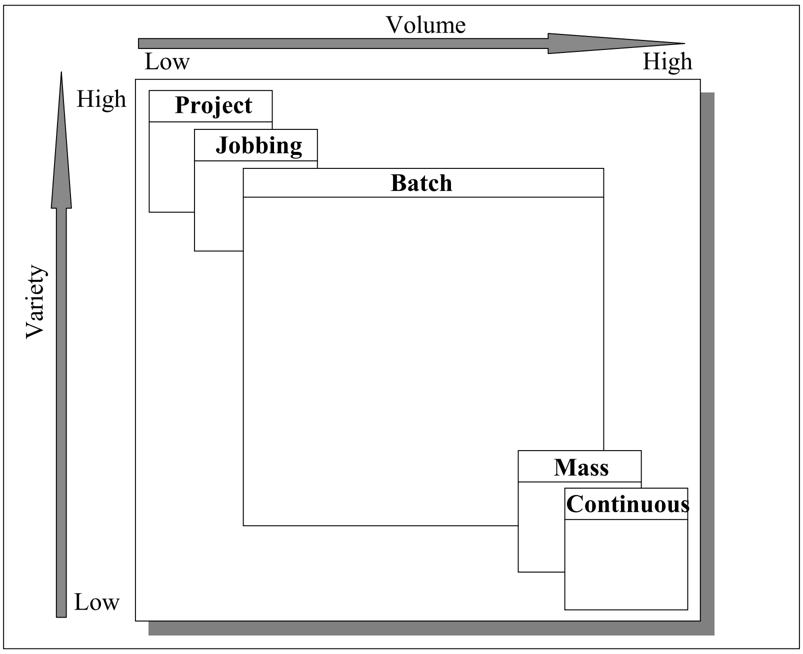



**Figure 1.3: Process types in manufacturing operations (Slack et al. 1998).**

The first stage involves the forecast driven production of the relatively narrow range of base products or modules. The second stage involves the order driven production of the broad range of finished product. Therefore the two processing stages are fundamentally different, the first stage requiring an approach akin to efficient ‘mass production’, and the second stage more of a flexible ‘jobbing shop’ approach as illustrated by the diagram in Figure 1.3.

The FPp approach contributes to manufacturing flexibility and cost efficiency by overcoming the trade-offs inherent in MTO and MTS. High manufacturing flexibility is achieved through overcoming the customisation versus order lead-time trade-off (Amaro et al. 1999) by retaining the opportunity to customise whilst minimising the order lead-time. High cost efficiency is achieved by overcoming the trade-off between the high economies of scale of speculative manufacture, and the low inventory costs and risks, associated with processing to order (Bowersox and Closs 1996).

**Table 1.1: Physically efficient versus market-responsive supply chains (Fisher 1997)**

| *Characteristic* | *Physically Efficient Process* | *Market-Responsive Process* |
|---|---|---|
| ***Primary Purpose*** | Supply predictable demand efficiently at the lowest cost | Respond quickly to unpredictable demand in order to minimise stock-outs, forced mark-downs, and obsolete inventory |
| ***Manufacturing Focus*** | Maintain high average utilisation rate | Deploy excess buffer capacity |
| ***Inventory strategy*** | Generate high turns and minimise inventory | Deploy significant buffer stocks of parts |
| ***Lead-time focus*** | Shorten lead-time as long as it doesn’t increase cost | Invest aggressively in ways to reduce lead-time |
| ***Approach to choosing suppliers*** | Select primarily for cost and quality | Select primarily for speed, flexibility and quality |

Fisher (1997) classifies products on the basis of their demand patterns into two primary categories, functional and innovative, claiming that each category requires a distinctly different kind of supply chain, as described in Table 1.1. Functional products (such as staples) satisfy basic needs which do not tend to change over time. They have stable and therefore predictable demand and long life cycles, and benefit from ‘efficient’ supply chain practices to improve productivity and reduce costs. On the other hand innovative products (found for example in the fashion apparel and personal computer industries) exhibit unpredictable demand due to short life cycles and the high variety typical of these products. They therefore benefit from 'responsive' supply chain practices that are geared to responding quickly to the unpredictable demand in order to minimise stock-outs, forced mark-downs, and obsolete inventory. The base product or modules in a FPp application can be likened to the 'functional' products and the finished product likened to the 'innovative' products. Hence, the implication for FPp is that the two types of supply chain can co-exist in series in the same factory (see CODP discussion in section 1.2.1).

The two processing stages could equally be labelled as 'lean manufacture' and 'agile supply' respectively. Agile supply assumes that the marketplace demands are volatile, whereas in a lean manufacturing environment the demand should be smooth leading to a level schedule.

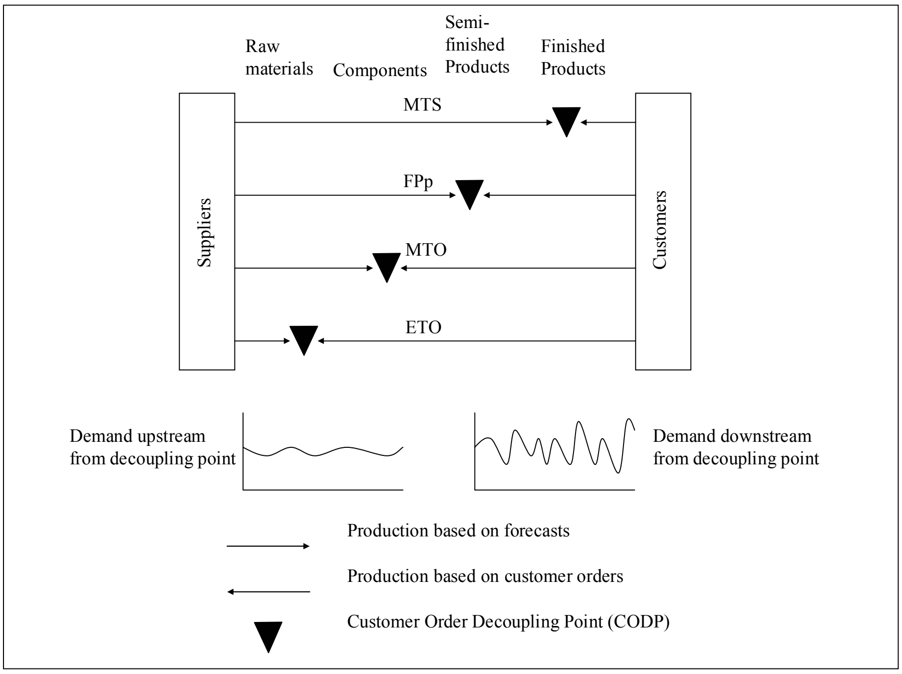



**Figure 1.4: Different locations for the decoupling point and its effect on demand (Naylor et al. 1999)**

When FPp is applied the CODP is at a semi-finished product (or module) stage as shown in Figure 1.4. This diagram summarises the effect of the CODP (here marked as a stock holding point) on demand. On the downstream side of the CODP demand is highly variable with a large variety of products. Upstream the demand is smooth with variety reduced (Hoekstra and Romme 1992). Naylor et al. (1999) conclude that the lean paradigm can be applied to the supply chain upstream of the decoupling point as demand is smooth and standard products are produced. Conversely the agile paradigm should be applied downstream from the decoupling point as demand is variable and the product variety increased. Combining agility and leanness in one supply chain with the strategic use of a decoupling point has been termed 'leagility' (Naylor et al. 1999a) and the literature relating to this is reviewed in section 2.5.1.

The dichotomy in manufacturing described here forms the basis of many of the logistical and operational implications of applying FPp as discussed in the literature review (Chapter 2). Managing this dichotomy in manufacturing within the same factory is a major challenge.

## 1.3 RESEARCH AGENDA

The principle of postponement has its roots in marketing (Alderson 1950) which is reviewed further in section 2.1. It has been developed in the logistics literature (for example Bowersox and Closs 1996) which has differentiated between the postponement of distribution (logistical postponement) and transformation processes (FPp). FPp is commonly cited in the logistics literature as contributing to improved supply chains and logistics systems (for example Scott and Westbrook 1991). In the operations management (OM) literature it is recognized as a method of achieving mass customization (for example Amaro et al. 1999) and more recently a new way of thinking about product design, process design and supply chain management (Yang and Burns 2003).

FPp is a phenomenon truly at the 'interface' (as understood by Voss 1995) between OM and logistics employing supply chain and manufacturing systems thinking. However, as is argued in the literature review in Chapter 2, the interface between these two disciplines has become blurred, so my perspective on OM and logistics needs to be stated. Here OM is primarily concerned with the development and management of value adding processes and the tools and techniques to support them (Harrison 1996). For this research project 'value adding processes' are confined to manufacturing transformation processes (as defined by Slack et al. 1998). Logistics on the other hand is primarily ‘concerned with getting products [and services] where they are needed when they are needed’ (Bowersox and Closs 1996).

This research project is confined to FPp applications where both postponed and generic processes are performed in the same location normally a factory. In this case two types of supply chain exist in series in the factory. The production of the generic product or modules is akin to an ‘efficient’ supply chain with the aim of lean manufacture. In contrast the postponed customisation is akin to a ‘responsive’ supply chain with the aim of agile supply. This introduces difficulties peculiar to FPp particularly in terms of manufacturing planning and inventory management which are normally geared towards MTO and/or MTS.

The benefits of FPp are widely appreciated and documented. However much less has been said about applying it. This research is primarily concerned with how FPp is applied within a manufacturing facility in terms of operations such as product design, process design, inventory management, location of CODP and manufacturing planning. This research is positioned at the interface between OM and logistics literature and therefore makes a contribution to both fields. It aims to provide managers with guidelines which indicate when FPp is justified and how it can be applied effectively.

### *1.3.1 Research Objectives*

Six objectives were identified which reflect the overriding goal of this project, which is to understand the operational implications of applying FPp in a manufacturing facility. The objectives have guided the execution of this research project and they are:

- To understand the reasons for the application of FPp as an alternative to MTO or MTS.

- To establish how products are selected for FPp - rather than MTO or MTS - particularly in relation to products demand profiles (demand mix, volume demand and demand variability) and production variety

- To determine the impact of FPp on customer service (order lead-time, ex-stock availability and delivery reliability) and demand amplification relative to MTO and MTS.

- To determine the product design implications of FPp particularly in terms of product modularity and standardisation.

- To identify and understand other major operational implications for a manufacturing facility which applies FPp. Particularly in terms of inventory management and the manufacturing planning and control system.

- To identify operational obstacles to the application of FPp in manufacturing facilities.

The objectives cover a broad field of enquiry which is both explanatory and exploratory in nature and is supported by the case study research design detailed in Chapter 3.

### *1.3.2 Contribution of Research to Operations Management Literature*

This research project aims to contribute knowledge to three areas of OM: non-MTS; mass customisation; and postponement.

Most OM literature classifies non-MTS companies into three types: assemble-to-order (ATO), MTO and engineer-to-order (ETO) (see for example New and Schejczewski 1995, Vollman et al. 1992). Clearly the key distinction between FPp and ETO or MTO is the location of the CODP (as discussed in section 1.2.1.). There are four key distinctions between FPp (as defined for this research) and ATO - although these two categories overlap. Amaro et al. (1999) point out that 'the literature addressing the needs of companies which produce in response to customers' orders is astonishingly modest'. The needs of the non-MTS sector have been neglected. However, over the four years since the Amaro et al. (1999) paper this sector appears to have received more attention.

Much of non-MTS literature addresses the needs of the traditional MTO sector and the bulk of these publications address issues related to manufacturing planning and control (for example Marucheck and McClelland 1986, Hendry and Kingsman 1989, Yeh 2000, Segerstedt 2002). A good proportion of the publications on MTO use mathematical models to address specific planning and control issues (for instance He and Jewkes 2000, He et al. 2002, Webster 2002). Very few papers address the specific needs of ETO (for example Eloranta 1992) or ATO (for example Wemmerlov 1984). Further in this literature MTO and ATO are considered *not* to be responsive - orders are promised on the basis of the availability of components and/or capacity rather than on the basis of a short, often standard, quoted lead-time as for FPp.

Mass customisation has been defined as ‘providing numerous customer chosen variations on every order with little lead-time or cost penalty’ (Ahlstrom and Westbrook 1999). Most of the literature on mass customisation is concerned with its strategic impact (for example Gilmore and Pine 1997, Pine et al. 1993 and 1995, Lampel and Mintzberg 1996, Kotha 1995, Westbrook and Williamson 1993). There are few publications concerning the operational implications of mass customisation (for example Pine 1993, Ahlstrom and Westbrook 1999, Swaminathan 2001, MacCarthy et al. 2003).

Recently a small body of OM literature has emerged that addresses postponement. A theoretical paper (Yang and Burns 2003) reviews research on postponement and concludes that still little is known about its application. Most of the OM literature on FPp uses mathematical or inventory models of postponement applications (for example Van Mieghem and Dada 1999, Aviv and Federgruen 2001a and 2001b, Ma et al. 2002, Ernst and Kamrad 2000). Most of these models consider delayed product differentiation applied to MTS approaches and are therefore not directly applicable to FPp. With the introduction of a CODP at the generic product stage they could be very useful in understanding some of the operational implications of FPp, such as capacity planning. This thesis contributes to this OM literature by using a case study research design to address ‘how’ FPp is applied.

This thesis aims to contribute knowledge to OM by considering the operational issues of applying FPp. This is a specific and responsive non-MTS approach to mass customisation distinct from existing documented categories, ETO, MTO and ATO. Unlike earlier literature this thesis focuses on the specific operational implications of mass customisation achieved by applying FPp within a manufacturing facility. A case study research design has been used to address the complexities of applying FPp. This exploratory work could aid the development of variable oriented inventory or mathematical models to simulate FPp and its operational implications. On a strategic level this research determines the reasons for applying FPp rather than MTO or MTS and how products (and customers) are selected.

### *1.3.3 Contribution of Research to Logistics literature*

This research project aims to contribute to our understanding of the conditions under which FPp is justified and specification of the appropriate FPp strategy (for example Zinn and Bowersox 1988, Zin, 1990a, Cooper 1993, Pagh and Cooper 1998, van Hoek 1998a, van Hoek et al. 1998). In this literature FPp is considered as an alternative strategy to MTS - not to MTO - and the guidelines are restricted to deciding an appropriate postponement strategy rather than its application. In general only FPp applications where the postponed processes are conducted in the distribution chain have so far been considered. When postponed processes are brought back into the factory substantially more complex processes are likely to be capable of postponement, as supported by the survey of companies in Holland conducted by Van Hoek (1998c).

This thesis aims to contribute to logistics knowledge by considering FPp applications where postponed processes are performed in the same location as the generic processes This research considers when FPp is a justified alternative to either MTS or MTO and the impact of FPp on customer service and demand amplification - both important supply chain issues. Further contributions are made by addressing the complex operational issues arising from taking the postponed processes back into the factory.

## 1.4 STRUCTURE OF THESIS

The literature review is presented in Chapter 2 and covers literature related to the application of FPp from three different fields - logistics, operations and engineering. The logistics and operations literature specifically addressing FPp (to which this research contributes) is reviewed separately. This chapter culminates in a conceptual model of FPp and a theoretical model predicting the outcome of applying FPp. Chapter 3 presents the hypotheses - extracted from the theoretical framework - which address the research question. This chapter also describes and justifies the research design in terms of the strategy and how it was operationalised. It concludes with the limitations of the design. Chapters 4, 5 and 6 detail the application of the research design in three different case companies. Chapter 4 describes the Pilot Study at Thomas Bolton which was conducted to develop the research methods and to firm up the hypotheses. Chapter 5 describes the case study at Brook Crompton where the three inventory management policies used in the manufacture of Direct Current motors were compared. Chapter 6 presents the study at Dewhurst which involved comparing the manufacture of three different products. The three case studies are compared in Chapter 7 in terms of their contexts, how FPp was applied, the flaws in the applications and the outcomes of applying FPp. The thesis ends with Chapter 8 which provides a summary of the research project, the contribution to knowledge made by the research and a discussion of the research limitations.

# CHAPTER TWO

# 2 Literature Review

The principle of postponement has its roots in marketing. It has been developed in the logistics literature, where FPp is commonly cited as contributing to more responsive supply chains. In the OM literature FPp is widely recognized as a method of achieving mass customization and more recently as an approach to product, process and supply chain design. FPp is a phenomenon which is positioned at the overlap of a number of subject areas and draws on a number of disciplines. Thus this research is positioned between logistics and OM and so employs supply chain and manufacturing systems thinking. It also draws on engineering literature which addresses product and process design for postponement - 'delayed product differentiation' (DPD). Hence three bodies of literature relating to FPp are reviewed in this chapter (as illustrated in Figure 2.1): logistics, operations and engineering.

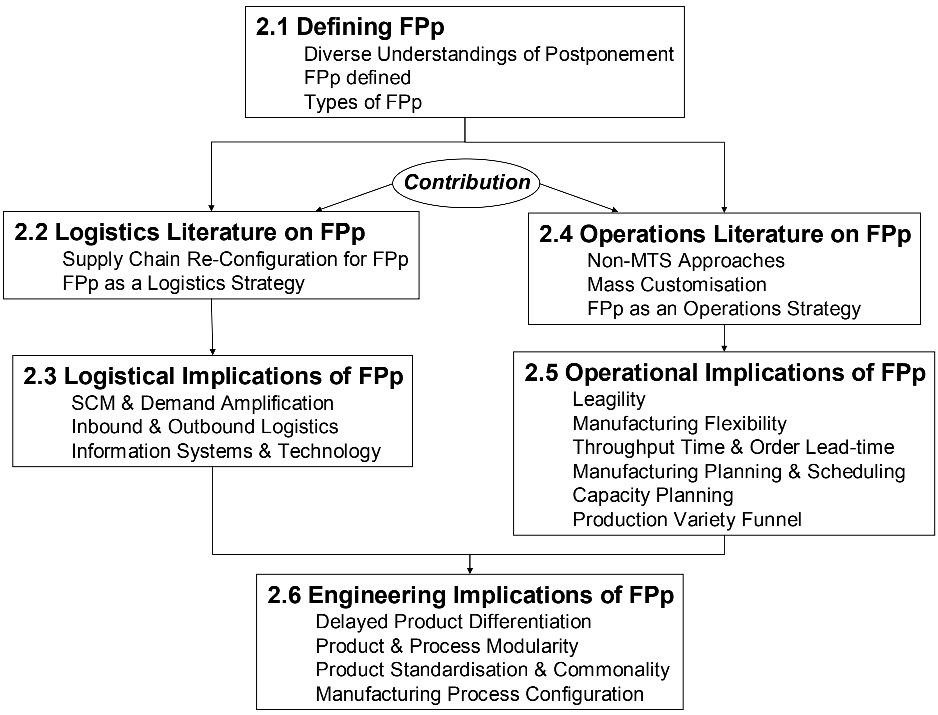



**Figure 2.1: Literature review structure.**

The purpose of this literature review is to:

- develop a working definition of FPp (section 2.1.2)
- identify gaps in the literature where a contribution could be made (sections 2.2 and 2.4)
- review the implications of applying FPp with a view to developing a conceptual model and theoretical framework from which the hypothesise can be extracted.

The literature review is structured as illustrated in Figure 2.1. An attempt has been made to distinguish between logistics and OM literature. However particularly in recent years the line between these two disciplines has become blurred. OM has become concerned with supply chain management (for example Yang and Burns 2003) and logistics is addressing product customisation (for example Walker et al. 2000). Journal subject classifications and an interpretation of OM and logistics have been used to guide the categorisation of the literature. Literature primarily concerned with 'the development and management of value adding processes and the tools and techniques to support them' (Harrison 1996) has been classified as OM literature. Literature primarily 'concerned with getting products [and services] where they are needed when they are needed' (Bowersox and Closs 1996) has been classified as logistics.

Section 2.1 provides a brief history of postponement and a critical review of existing postponement definitions which was the basis for the working definition of FPp used for this research.

Section 2.2 reviews logistics research addressing FPp which can be split into two areas. The first addresses the configuration of supply chains for FPp where factories and warehouses are treated as 'black boxes'. The second area is a small body of research addressing when FPp is the justified approach by considering the product, market and process characteristics that favour FPp. This thesis contributes to the latter area - but not the former - since it is concerned with the operational implications within the factory, but not the configuration of factory and warehouse sites.

Logistics research associated with the implications of applying FPp is reviewed in section 2.3. FPp is viewed in the context of Supply Chain Management (SCM), in particular its effects on demand amplification. The implications for both inbound and outbound logistics are also considered focusing mainly on the postponed process. Finally the information system and technology implications of FPp are considered.

Section 2.4 reviews OM research addressing concepts closely related to FPp. The first part reviews research on non-MTS approaches, of which FPp is an example. The second part considers research on mass customization, for which FPp is widely recognized as a possible approach. In the third part recent research is reviewed which considers the application of postponement as an operations strategy. This thesis makes a contribution to all three areas of OM research.

Section 2.5 reviews the OM research relating to the various operational implications of applying FPp. Manufacturing flexibility in its various forms is considered - in particular mix flexibility required for the postponed process. Throughput time and order lead-time are discussed in relation to throughput efficiency. Approaches to manufacturing planning and production scheduling suitable for FPp applications are presented. Capacity planning issues are addressed particularly with respect to the provision of excess capacity at the postponed process. Finally the production variety funnel, central to the conceptual model, of FPp is introduced.

Engineering research relating to FPp is reviewed in section 2.6. Delayed product differentiation (DPD), which can be an approach to product and process re-design for FPp, is introduced. The three approaches to DPD are discussed in relation to FPp: product and process modularity; product standardization and component commonality; and manufacturing process re-structuring.

This chapter concludes with the conceptual model of FPp, the theoretical framework and the gaps in logistics and OM research to which this thesis makes a contribution.

## 2.1 DEFINING FORM POSTPONEMENT

This section provides a brief history of postponement and a critical review of existing postponement definitions which was the basis for the working definition of FPp used for this research.

The concept of postponement is first introduced in marketing by Alderson (1950) who argues that postponement could be used to reduce risk and uncertainty costs associated with the differentiation of goods. He claims that differentiation could occur in the product itself or the geographical dispersion of the inventories and offers the principle of postponement, which advocates:

> *'postpone changes in form and identity to the latest possible point in the marketing flow; postpone changes in inventory location to the latest possible point in time.'*

Alderson (1950) argues that savings in costs related to uncertainty would be achieved 'by moving the differentiation nearer to the time of purchase', where demand presumably would be more predictable. Later Bucklin offers the converse of postponement, the principle of speculation, which states:

> *'changes in form, and the movement of goods to forward inventories, should be made at the earliest possible time in the marketing flow in order to reduce the costs of the marketing system.'*

Bucklin (1965) recognises that postponement has its limitations and there are trade-offs to consider. He argues that speculation permits the goods to be ordered in large quantities therefore improving the economies of scale for manufacturing. To express the limitation of postponement he proposes a combined principle of postponement-speculation:

> *'a speculative inventory will appear at each point in a distribution channel whenever its costs are less than the net savings to both buyer and seller from postponement.'*

Following the work of Alderson and Bucklin it was some time before postponement was practised. There are a number of theories as to why this was the case. Van Hoek (1998a) concludes that new technologies (information and communication technology), operating circumstances (deregulation in Europe), and new organisational forms (integrated networks) have recently enabled the application of postponement (van Hoek et al. 1996 and 1998).

### *2.1.1 Diverse Understandings of Postponement*

In the late 1980s postponement became known as a logistics strategy (Cooper 1993). Subsequently much of the research over the last decade of the 20th century regarding postponement appears in the logistics literature. In a key paper by Zinn and Bowersox (1988) which attempted to operationalise the postponement-speculation principle the following definition of postponement was given:

> *'Postponement consists of delaying movement or final formulation of a product until after customer orders are received.'*

This definition is more specific than Alderson's stating that the postponed activities should take place *after the receipt of customer orders*. Two main types of postponement (implied by Alderson's original definition) are defined, 'form or manufacturing postponement' and 'logistical or time postponement'. As discussed in Chapter 1 logistical postponement falls outside the scope of this research therefore this chapter focuses on form postponement.

Zinn and Bowersox (1988) offer the following definition of FPp:

> *'Form Postponement proposes that under specific situations that the least risky procedure may be to send products to the warehouses in a semi-finished state for final processing after the customer order is received.'*

This definition is narrow in scope stipulating that the postponed process takes place in a warehouse and is restricted to final processing. 'Postponed manufacturing' (van Hoek, 1998a) is a very similar concept to this, but requires that the postponed process take place in a 'facility close to the customer separated from the manufacturing of semi-finished or generic products or components'. The requirement that the postponed process take place in the distribution chain, normally a warehouse, is the inherent weakness in these definitions as argued in section 2.1.1 below.

The engineering literature has a very different view of logistical postponement and FPp. Lee and Billington (1994) define logistical postponement in the same way as Zinn and

Bowersox (1988) define FPp. Further 'form' postponement is defined to exist only when the product design is standardised so the differentiation step no longer exists and therefore differentiation is effectively postponed. The engineering literature which focuses on design for postponement (for example, Lee and Tang 1997, Garg and Tang 1997, Lee 1996) uses the term 'delayed product differentiation'. This can be achieved through standardisation, modular production, or process restructuring and is reviewed in detail in section 2.6.

Recently a host of new postponement definitions have emerged in the OM literature. For example Brown et al. (2000) define 'product postponement' as 'products are designed so that the product's specific functionality is not set until after the customer receives it'. This involves the customer configuring a standardised product upon receipt and is classified as a 'standardisation' strategy (as described in section 2.6.3). Brown et al. (2000) also use the term 'process postponement' to describe the creation of a generic part in the initial stages of the manufacturing process which is later customised to give the finished product. This fits well with the working definition of FPp used for this research unlike other definitions in the OM literature. For example Van Mieghem and Dada (1999) consider postponement of different operational decisions: 'price postponement' involves delaying setting the price; and 'production postponement' involves delaying production until an order has been received (MTO).

In the logistics literature the definition of 'FPp' is considerably extended by Van Hoek (van Hoek 1998c, van Hoek et al. 1996 and 1998):

> *'Form Postponement involves the delaying of activities that determine the form and function of products until orders are received'*

Later Van Hoek (2001) states:

> *'postponement means delaying activities in the supply chain until customer orders are received with the intention of customising products, as opposed to performing those activities in anticipation of future orders'.*

These definitions do not specify the location of the postponed process therefore these activities may take place at the manufacturing plant or in the distribution chain. Further the postponed processes are described as 'activities that determine the form and function of products' or customising activities. For any given product the most upstream activity that may be postponed is the engineering or design of the product. Therefore these definitions include ETO and MTO (as defined by Amaro 1999, Browne et al. 1996) as approaches to postponement. This appears to be a commonly used understanding of postponement in the OM literature (see for example Yang and Burns 2003).

### *2.1.2 Defining FPp*

The literature provides no consensus on a clear definition of FPp, instead there is a host of definitions expounding different ideas. Much of the research on FPp uses one of two FPp definitions neither of which appears appropriate. The Zinn and Bowersox (1988) definition requires the postponed process to take place in the distribution chain and the van Hoek (1998c, 2001) definition encapsulates ETO and MTO as approaches to FPp. First consider the Zinn and Bowersox (1988) definition. The requirement that the postponed process take place in the distribution chain, normally a warehouse, is an inherent weakness for three reasons.

Firstly this definition does not reflect what several manufacturing companies are actually doing – for instance many manufacturers conduct the postponed process in the same location as the generic processes:

- Sony Manufacturing (UK) at Bridgend applied FPp to television manufacture (Ferguson 1989) by designing a 'Eurochassis' (the base of the television to which the PCBs and other components were fitted) which was common to all its products. Only at a late stage in the manufacturing was the Eurochassis tailored specifically for individual customer orders.

- Courtaulds Hosiery (Aristoc plant in Northern Ireland) manufactured tights in two gauges of yarn, in five sizes and in twelve colour shades to provide 120 different variants (New and Skipworth 2000). FPp was applied to both the tights themselves and the packaging. The tights were knitted from natural yarn and over-dyed to customer order, and the packaging (which suffered from the same level of variety) was standardised and over printed to order.

- Xerox applied FPp to their office digital products in 1997 at the Gloucester plant (Christopher 1998). A minimal level of 'neutral' finished goods were made to stock and only configured to customer order.

- Benetton knitted the jumpers in natural yarn to stock and subsequently dyed them to customer order all in their main plant in Italy (Harvard Business School 1985).

Other examples of FPp require the postponed process be performed at the retailers. Instead of stocking the full range of paint colours for each variant some retailers stock the generic paint with a variety of pigments and mix them to specific customer orders (Feitzinger and Lee 1997). Sunoco gasoline stations apply a similar principle (Bowersox and Closs 1996). Here a standard low octane gasoline was stocked and mixed with additives to customer order to make higher octane grades of unleaded petrol.

Secondly conducting postponed processes in warehouses tends to restrict such processes to extremely simple ones for two main reasons. Firstly they would be required to take place at multiple sites ensuring that only low capital manufacturing installations are viable. Secondly the lack of proximity to the main manufacturing plant, and the expertise it offers, would dissuade many manufacturers from conducting highly technical or critical processes in a warehouse. Many examples support this view:

- the postponed process conducted in the warehouses by Motorola consists of programming the frequencies into the radios and labelling them accordingly (Andel 1997).

- Hewlett-Packard manufactured generic Deskjet Printers at their Vancouver plant and shipped them to there distribution centres (Europe, Asia etc.) for 'localisation' (Lee et al. 1993). Here the printers were merely 'box kitted' with the correct power supply module and manual to order (Davis and Sasser 1995).

- Caterpillar developed a manufacturing and distribution system whereby fork lift trucks were produced offshore and options, such as lifts and forks later attached against customer orders in a US warehouse.

Thirdly this narrow definition is flawed because it may not be *necessary* to perform the postponed processes in a warehouse, which offers greater proximity to the customers than the manufacturing facility. The key is getting the 'time' right between commencing the postponed process and the receipt of the product by the customer not the 'distance'. Therefore, the appropriate location for these processes depends on the customer required order lead-time and the speed of final distribution transport according to the 'point of fulfilment' described by Inger et al. (1995).

Considering the van Hoek's (1998c, 2001) definition which encapsulates ETO and MTO as approaches to FPp, it is acknowledged that:

> *'the vision of manufacturing postponement is one of products being manufactured an order at a time with no preparatory work or component procurement until exact customer specifications are fully known and purchase commitment is received' (Bowersox and Closs 1996).*

However, in practice there is a trade-off between the high economies of scale achievable through speculative manufacture and the low inventory costs and risks resulting from processing to order - if the required responsiveness is to be achieved without sacrificing efficiency (Bowersox and Closs 1996). Bowersox and Closs (1996) state that the ideal application of postponement is to manufacture a standard base product in sufficient quantities to realise economies of scale, while deferring finalisation of features (such as colour) until customer commitments are received. ETO and MTO are not encapsulated by this understanding of FPp.

The above arguments culminated in the following working definition that has been used for this research:

> *'**FPp** is the delay, until customer orders are received, of the final part of the transformation processes, through which the number of different product items proliferates and for which only a short time period is available. The postponed transformation processes may be manufacturing processes, assembly processes, configuration processes, packaging, or labelling processes.'*

It broadens the Zinn and Bowersox (1988) definition by *not* stipulating the geographical location of the postponed process. It acknowledges that the postponed process may take place not only at a *warehouse* but at a *factory* (as in 'bundled manufacturing' defined by Cooper 1993) or even at the *retailers*, and these locations may be near to or remote from the customers. Yet it is more restricting than the van Hoek (1998c) definition by confining FPp to the postponement of 'the final part of the transformation process'.

### *2.1.3 Types of Form Postponement*

The most prevalent types of FPp are those defined by Zinn and Bowersox (1988) and listed in Table 2.1. They are distinguished by certain product characteristics and which process is postponed. However, the distinction between assembly and manufacturing postponement lacks clarity. The degree of warehouse assembly is a basic distinction where manufacturing postponement requires a complete job-shop strategy in the warehouse. A further distinction is the number of locations from which parts are shipped – in assembly postponement parts are shipped from a single location, whereas in manufacturing postponement parts are shipped from multiple locations.

**Table 2.1: Types of FPp summarised from Zinn and Bowersox (1988).**

| *Postponement Type* | *Product characteristics* |
|---|---|
| ***Labelling*** | The product is marketed under different brand names |
| ***Packaging*** | The specific product is marketed in different package sizes |
| ***Assembly*** | A base product with a number of common parts is sold in a number of configurations |
| ***Manufacturing*** | Parts are shipped to the warehouse, where manufacturing is completed to customer order |

Lee and Billington (1994) focus on high technology products and build on the definitions proposed by Zinn and Bowersox (1988). They define five types of postponement based on the manufacturing steps generally required for high technology products, as summarised in Table 2.2.

The postponement types defined by Zinn and Bowersox (1988) are applicable to consumer products whereas the classification made by Lee and Billington (1994) is suitable for high technology products. In essence Lee and Billington (1994) built on Zinn and Bowersox (1988) definitions by distinguishing between different types of assembly postponement, namely integration, customisation and localisation postponement.

In his evaluation of logistics strategies for global businesses Cooper (1993) identifies 'deferred assembly' and 'deferred packaging' as postponement strategies. These are equivalent to the assembly, packaging and labelling postponement types defined by Zinn and Bowersox (1988). Further Cooper (1993) defines 'bundled manufacturing' as another postponement strategy, where the product is designed so customisation can take place at the latest possible stage of the production process in the manufacturing plant. This is not classed as FPp in terms of the Zinn and Bowersox (1988) definition, however it is according to the broader definition proposed by van Hoek (1998c) and the working definition used for this research.

**Table 2.2: Types of FPp summarised from Lee and Billington (1994).**

| ***Postponement Type*** | ***Manufacturing step characteristics*** |
|---|---|
| ***Manufacturing*** | Fundamental step in which a core of the product is made. Usually a small number of products are made at this stage |
| ***Integration*** | The main core of the product is combined with key sub assemblies (e.g. different circuit boards which are integrated into the engine), to become different product versions |
| ***Customisation*** | Further assembly of the product with different accessories to form distinct product choices, e.g. different software or memories. |
| ***Localisation*** | Each of the product options so far is differentiated to suit the local requirements of different regions or countries, e.g. different power supplies |
| ***Packaging*** | Not all product options will require different packaging, but sometimes the peripherals may be different e.g. toner cartridges |

***Conclusion:*** Neither the Zinn and Bowersox (1988) or Lee and Billington (1994) definitions of FPp types are particularly clear or generalisable to a wide range of products. Five different types of FPp are proposed here based on a characterisation of the postponed process as shown in Table 2.3

**Table 2.3: FPp classification used for this thesis.**

| ***FPp type*** | ***Postponed Process Characteristic*** |
|---|---|
| ***Manufacturing*** | Irreversible transformation of the product, often involving the input of some homogenous materials, such as the input of polymer granules to extrusion. |
| ***Assembly*** | Physical joining of components or modules, which is often reversible. |
| ***Configuration*** | Minor changes to the product that do not involve changing its physical appearance, like loading the software to a computer, or inputting an identification code into a mobile telephone. It does not include stock picking different combinations of items, which do not require physically joining or involve some transformation process. |
| ***Packaging*** | Packaging of a product supplied in different package sizes or styles. This does not include the postage over-packaging of a customer order. |
| ***Labelling*** | Labelling of a product often sold under different brand names |

## 2.2 LOGISTICS LITERATURE ON FORM POSTPONEMENT

This section reviews the logistics literature addressing FPp which can be split into two areas. The first addresses the configuration of supply chains for FPp where manufacturing sites (factories or warehouses) are treated as 'black boxes'. The second area is a small body of literature addressing when FPp is the justified approach by considering the product, market and process characteristics that favour FPp.

### *2.2.1 Supply Chain Re-Configuration for Form Postponement*

The appropriate location for the postponed process (and the associated speculative aggregate inventory) is determined not only by supply chain design but also by the design of the product (New and Skipworth 2000). In a theoretical study Cooper (1993) evaluated postponement strategies for global brands. He made deductions regarding supply chain configuration for FPp in relation to product design or variety:

- where the formulation and peripherals are global FPp is not favoured, because the product line is very narrow.
- where the formulation differs from market to market, but the peripherals are standard, FPp taking place in the factory is favoured – 'bundled manufacturing'
- where the peripherals differ from market to market FPp is favoured where the postponed processing is performed in the distribution chain.

Cooper (1993) assumes that the peripherals significantly increase the product volume, and therefore transportation costs are reduced, by transporting products without peripherals to the warehouse and packaging them there.

Supply chain design issues which determine the location of the postponed process include the Portfolio Effect which means that centralising inventories in fewer locations always results in a reduction of safety stocks. Zinn (1990a) shows that the Portfolio Effect is maximised whenever the sales correlation between two inventory locations is highly negative, and the proportional difference in demand variability is small. However Inger et al. (1995) claims that the location of the postponed process or 'point of fulfilment' is still critically dependant on the lead-time the customer is prepared to accept.

Van Hoek (1998a and 1998b) and Van Hoek et al. (1996 and 1998) built on the ideas put forward by Cooper (1993) in a major study into the application of 'postponed manufacturing' (FPp where postponed processing is performed in the distribution chain) in European supply chains. This study involved eight case studies and provided three major contributions concerned with the reconfiguration of the supply chain for FPp:

- Firstly customer service and responsiveness considerations are usually the primary drivers for postponed manufacturing applications. The implementation of 'postponed manufacturing' requires the reconfiguration and design of the outbound logistics or downstream supply chain. The starting point in the change process and organisational heritage (particularly whether the company is American or European) has a significant effect on the supply chain reconfiguration process.

- Secondly a postponement trade-off framework was developed. It suggests what types of postponement are viable in relation to: the position in the supply chain of the manufacturing company; and the geographical scale at which final manufacturing takes place. This framework did not however consider FPp where all processing takes place in the factory as an option.

- Thirdly a number of tools and methods are provided to aid the reconfiguration of supply chains for 'postponed manufacturing'. For European companies a calculation model is suggested while the logistics strategy framework developed by O'Laughlin et al. (1993) is proposed for American companies.

***Conclusion:*** so far the literature has treated manufacturing sites (factories or warehouses) as 'black boxes'. Further it largely ignores FPp in the factory and focuses on cases where variety is added in the distribution chain. This thesis is concerned with operations within the factory - rather than the configuration of manufacturing in warehouse facilities - therefore it makes no contribution to this literature.

### *2.2.2 Form Postponement as a Logistics Strategy*

A small body of logistics literature addresses the various characteristics – such as product, market, demand - that favour FPp. It is argued that FPp is not always the most cost-effective approach to manufacturing and distribution, and the identification of characteristics that favour FPp will provide managers with guidelines as to when FPp is justified (Zinn and Bowersox 1988).

A leading article by Zinn and Bowersox (1988) explores the impact of changes in physical and demand product characteristics, on the cost of distribution (inventory carrying plus transportation costs) using FPp, compared with using MTS with anticipatory distribution. Four normative cost models were used, each based on one of the four types of FPp defined by Zinn and Bowersox (1988): manufacturing, assembly, packaging and labelling (see section 2.1.3.). Demand uncertainty, product value, product variety, and in the case of postponed assembly, the cube or volume reduction (obtained by transporting products unassembled to the warehouse), were all found to favour FPp. Only volume demand at generic level showed little or no significant support for FPp. Zinn (1990b) summarised this contribution by stating that generally postponement opportunities ‘emerge as large errors in demand forecasting increasing the cost of distribution’, and are ‘greater for products of high unit value, because such products have high inventory carrying cost’.

A number of assumptions are made in the Zinn and Bowersox (1988) study that limit its generalisability:

- First, and most notably the data used concerned products from the same company, which appear from the data to be of a similar nature, however details regarding product type is not given.

- Second, the segment of the distribution channel covered by the cost models is from the manufacturing plant exit to the warehouse exit. Therefore, the modelling assumes that the product design does not change and it does not take into account the effect on manufacturing costs of relocating production into warehouses. It is impossible to judge if this is realistic, however it is possible to say that this assumption limits the generalisability of the study to cases where this assumption holds.

- Third, it is assumed that postponing either the assembly, or manufacturing processes until an order is received, results in an increase in average delivery time (order lead-time), and subsequently lost sales. It can be argued that the increased availability of product variants – a potential benefit of FPp (due to customising only to order) - may negate the effects of lost sales due to increases in order lead-time.

The study by Zinn and Bowersox (1988) may be difficult to generalise. However their findings that demand uncertainty, product value, and product variety favour FPp is supported by other work (Zinn 1990a, Cooper 1993, van Hoek 1998a). Zinn (1990a) further explores the impact of product demand characteristics on the viability of FPp by developing heuristics to estimate the impact of FPp on safety stocks. Risk pooling techniques are used because the risk related to the demand uncertainty for each product item is pooled together when FPp is applied. The heuristics developed indicate that safety stock savings from FPp are higher when:

- demand for individual items is independent of each other or negatively correlated,

- the number of products in the product line is greater, (however the savings stabilise when the number of items exceeds eight) or

- the standard deviation of demand for items in the product line are approximately equal.

Lee and Billington (1994) also showed that inventory savings are greater where the demands for different products are negatively correlated.

In the above studies 'demand variability' is used to indicate 'demand uncertainty' (Zinn and Bowersox (1988), and Zinn (1990). Here standard deviation of demand is used as a measure of 'demand uncertainty'. Bhattacharya et al. (1995) clearly distinguishes between variability and uncertainty of demand. *Variability* measures the changes in demand over a given sequence of time buckets, forecasted at a given point in time. It can be measured using the coefficient of variation (CV), the ratio of the standard deviation to the average demand. *Uncertainty* measures the changes in demand for a given time bucket as it moves in time and approaches the delivery due date. This raises the question whether it is valid to use demand variability as an indication of uncertainty. However setting aside this consideration existing theory supports the proposal that demand uncertainty at finished product level favours FPp. Traditionally in a MTS situation finished inventory is used as a buffer against demand uncertainty (Newman et al. 1993). FPp eliminates this finished product safety stock, therefore the greater the demand uncertainty the greater the reduction in safety stock due to FPp.

Chiou et al (2002) empirically examine four types of FPp proposed by Zinn and Bowersox (1988) (manufacturing, assembly, packaging and labelling) against Taiwanese Information Technology (IT) firms. They find that these FPp types are practiced by the Taiwanese IT firms and that:

- products characterised by high levels of customisation and modular designs benefit from assembly FPp
- products with expensive key components benefit from labelling and packaging FPp but not necessarily assembly or manufacturing FPp
- products with short product life cycles benefit from manufacturing FPp

In a theoretical study Cooper (1993) evaluates postponement strategies for products with global brands. He explores the impact of two further product characteristics on the application of FPp as shown in Table 2.4.

Cooper (1993) argues that where either the formulation or peripherals, or both, are not global (i.e not common to all markets) FPp is favoured. When the product formulation differs from market to market, but the peripherals are standard, ‘bundled manufacturing’ is favoured - where the postponed processes take place in the factory. However when the peripherals are not standard ‘deferred FPp’ is favoured, where the postponed process takes place in the theatre warehouse. Cooper (1993) assumes that the peripherals significantly increase the product cube or volume, and therefore transportation costs are reduced, by transporting the products without peripherals to the warehouse and packaging them there.

**Table 2.4: The impact of product brand, formulation, and peripherals on postponement strategies for global products (Cooper 1993)**

| | ***Unicentric*** | ***Bundled Manufacturing*** | ***Deferred Assembly*** | ***Deferred Packaging*** |
|---|---|---|---|---|
| ***Product characteristics – are they common to all markets, i.e. global?*** | Fully centralised production and distribution | Design product so that customisation can take place at latest possible stage of production process | Final configuration of product at theatre warehouse | Labelling and packing at theatre warehouse |
| ***Brand*** | Global | Global | Global | Global |
| ***Formulation*** | Global | NOT Global | NOT Global | Global |
| ***Peripherals (labels, manuals, packaging etc.)*** | Global | Global | NOT Global | NOT Global |

Pagh and Cooper (1998) further this work by generalising the manufacturing processes so the postponed process can be any final processing not just assembly packaging or labelling. They also consider logistical postponement as well as the strategies identified by Cooper (1993) as shown in Figure 1.2, section 1.2.2. They provide a diagnostic and normative framework for selecting the 'postponement and speculation' strategy which focuses on the downstream supply chain from factory to end customer. The decision determinants in the framework include various characteristics: product (e.g. life cycle stage), market and demand (e.g. delivery frequency) and manufacturing and logistics (e.g. economies of scale).

Van Hoek (1998a) and van Hoek et al. (1998) collate factors that favour 'postponed manufacturing' from previous research (Council of Logistics Management 1995, Cooper 1993, Zinn and Bowersox 1988 and Van Hoek and Commandeur 1995) as shown in Table 2.5. He uses the following definition:

> *'Postponed manufacturing involves the final manufacturing of products in response to customer orders, performed in a facility close to the customer (separated from manufacturing of semi-finished or generic products and components) followed by shipment to the customer.'*

Van Hoek (1998a) and van Hoek et al. (1998) assess these characteristics as peripheral issues of a major research project involving eight case studies of different companies applying 'postponed manufacturing' in Europe. He finds these characteristics are generally evident in the eight case companies.

**Table 2.5: Market, product and process characteristics that favour postponed manufacturing (van Hoek 1998a).**

| *Characteristics* | *Effect of 'Postponed Manufacturing'* |
|---|---|
| ***Market*** | |
| - Short product life cycle | - Reduced risk of obsolete inventories |
| - High sales fluctuations | - Reduced inventory levels |
| - Short and reliable lead-times required | - Improved delivery service |
| - Price competition | - Lowered cost levels |
| - Varied markets and customers | - Improved targeting, segmentation, and positioning of product and sales |
| ***Product*** | |
| - Specific formulation of products | - Improved customisation |
| - Specific peripherals, such as labels, packaging and instruction manuals | - Improved customisation |
| - High value density of products | - Reduced pipeline expenses and inventory carrying costs |
| - Product cube and/or weight increases through customisation (distributed postponement only) | - Reduced transportation and inventory carrying costs |
| - Modular product design | - Rapid final manufacturing at low processing costs |
| - High commonality of modules | - Lowered inventory levels and reduced risk of obsolete inventories |
| ***Process*** | |
| - Feasible to decouple primary and postponed operations | ( a precondition) |
| - Limited complexity of customising operations | - Limited loss of economies of scale through postponement |
| - Sourcing from multiple locations | - Direct bulk shipments of modules |

Van Hoek (1998a) and van Hoek et al. (1998) observes that the requirement for short and reliable lead-times favours postponed manufacturing, which improves delivery service compared to MTS (see Table 2.5). It is argued that while FPp may improve product (ex-stock) availability, and allow greater product customisation (Amaro et al. 1999) it is unlikely to reduce the standard order lead-time. Van Hoek does not consider

FPp as an alternative to MTO. However, it can be argued that FPp will reduce the order lead-time and improve delivery reliability because only the final processing is 'to-order' reducing the risk of lateness.

Six out of the eight case studies (van Hoek 1998a and van Hoek et al. 1998) exhibit customisation processes of low complexity. Van Hoek argues that the more complex the postponed processes the greater the losses in economies of scale by only processing to order (refer to Table 2.5). Therefore limited complexity of the postponed customisation process favours 'postponed manufacturing'. However, in the survey of companies based in Holland conducted by van Hoek (1998c) and reviewed below a positive correlation between final manufacturing complexity and application of FPp was found. This is most likely attributable to the use of a broader definition of 'form postponement' in this survey. Here FPp includes ETO and MTO and also applications where the postponed process takes place in the factory. It is argued that for FPp applications where the postponed process is performed in the distribution chain (van Hoek's 'postponed manufacturing') the postponed activities are relatively simple. Conversely when the postponed processes are brought back into the factory it is argued that substantially more complex processes are likely to be postponed.

Van Hoek (1998c) studied characteristics that favour 'form postponement' in a survey of companies based in Holland from the electronic, automotive, food and clothing industries. As expected various characteristics such as product modularity, high commonality of components, demand uncertainty and variability positively correlate to the extent of FPp application. Surprisingly, however, the 'changes in competition and production' indicated by such items as 'short product life cycles', and 'competitors actions are difficult to predict', and product cube and variety increase during final manufacturing are negatively correlated with postponement. These findings contradict previous research. Once again this is most likely attributable to the use of the broader definition of 'form postponement' which is significantly different to the concept of FPp used by previous research (Zinn and Bowersox 1988, Zinn 1990, Cooper 1993).

***Conclusions:*** Characteristics that favour FPp are identified to provide managers with guidelines as to when it is justified and what is the right FPp strategy. However FPp is only considered as an alternative strategy to MTS (not MTO) and the guidelines are restricted to deciding the appropriate postponement strategy and do not consider its application. Further only FPp where the postponed processes are conducted in the distribution chain is generally considered. When the postponed processes are brought back into the factory it is argued that substantially more complex processes are likely to be postponed. This thesis contributes to this body of literature by considering FPp as an alternative to both MTS and MTO and how it is applied.

## 2.3 LOGISTICAL IMPLICATIONS OF FORM POSTPONEMENT

Logistics literature associated with the implications of applying FPp is reviewed in this section. FPp is viewed in the context of Supply Chain Management, in particular its effects on demand amplification. The implications for both inbound and outbound logistics are also considered, particularly focusing on the postponed process. Finally the information system and technology implications of FPp are considered.

### *2.3.1 Supply Chain Management and Demand Amplification*

The concept of Supply Chain Management (SCM) was introduced in the early 1980s (Oliver and Webber 1982). It referred to the management of materials across functional boundaries within an organisation, such as purchasing, manufacturing, sales and distribution. The SCM concept has now been externalised beyond the boundary of the firm to a more holistic concept of managing operations across inter-organisational boundaries (Womack et al. 1990 and Christopher 1998). SCM has been defined in numerous ways, most relevantly, as an 'integrative philosophy to manage the total flow of a distribution channel from supplier to the ultimate consumer' (Ellram and Cooper 1990).

More recently supply chains have been defined as single routes through supply networks, which contain upstream suppliers and supplier's suppliers and downstream customers and customer's customers as viewed by one firm (Harland 1996, and Slack et al. 1998). Figure 2.2 shows a supply chain network structure, as depicted by Slack et al. (1998). This research project focuses on 'the operation' and its capabilities to meet the demands of the first tier customer network using FPp.

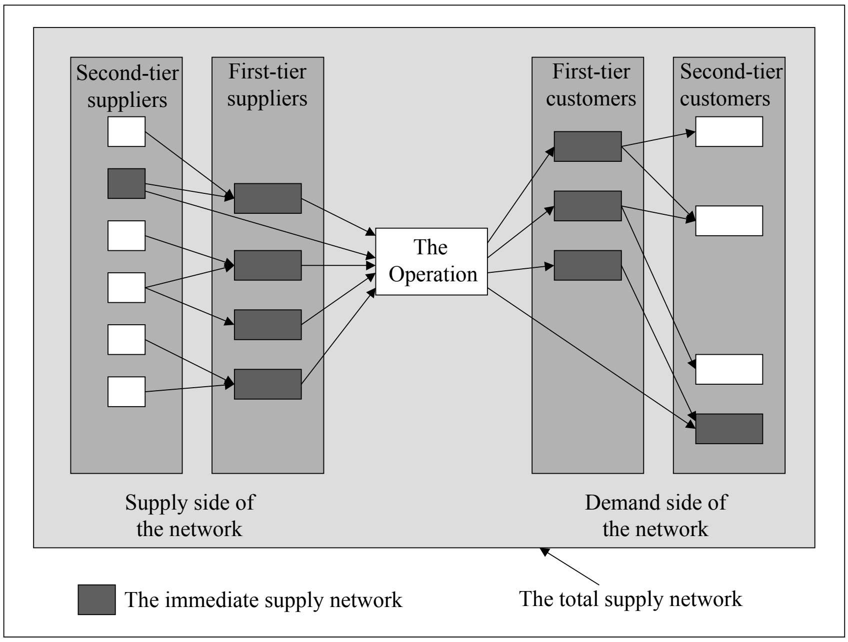



**Figure 2.2: Total and immediate supply networks (Slack et al. 1998)**

SCM is a systems approach to viewing the channel as a whole rather than as a set of fragmented parts according to Ellram and Cooper (1990). The aim of SCM with respect to inventory management is 'minimising inventory and meeting the firm's customer service objectives' (Ellram and Cooper 1990). This is achieved by managing inventory throughout the entire supply chain from the supplier to the end consumer. These core aims of SCM are not traditionally compatible, in fact many authors identify high customer service, low inventory investment, and low unit cost, as conflicting goals (for example Stevens 1989, Inger et al. 1995).

**Table 2.6: Conflicting goals of lean logistics (Inger et al. 1995)**

| *Tactic* | *Customer Service* | *Inventory Investment* | *Manufacturing Unit Cost* |
|---|---|---|---|
| ***Large Manufacturing Batches*** | Low | High | **LOW** |
| ***Focus on Customers*** | **HIGH** | High | High |
| ***Reduce Inventory*** | Low | **LOW** | **LOW** |
| ***Lean Logistics*** | **HIGH** | **LOW** | **LOW** |

**'HIGH' or 'LOW'** is Good news 'High' or 'Low' is bad news

Inger et al. (1995) illustrate how the goals of high customer service, low inventory investment and low manufacturing cost are in conflict in three different tactics, but are achievable in 'lean logistics (as shown in Table 2.6). Of course in practice the results of applying these various tactics - particularly 'focus on customers' and 'lean logistics – are not so predictable. Product characteristics such as value and variety can have a significant impact on a company's ability to achieve these goals.

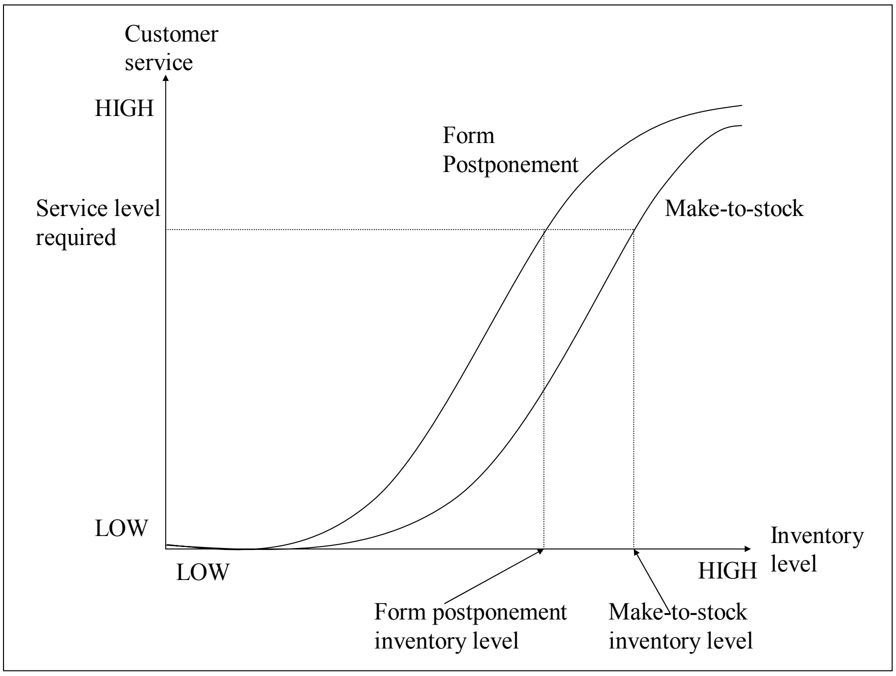



**Figure 2.3: Customer service versus inventory level trade-off curves for FPp and MTS approaches (adapted from Jones and Riley 1985)**

FPp (as an alternative to MTS) contributes to the SCM goal of 'minimising inventory and meeting the firm's customer service objectives' by delaying the differentiation of a product until an order is received. Thus the speculative inventory between trading partners in a supply chain is reduced, while product availability is likely to be improved, and order lead-time kept short. This is illustrated by the chart in Figure 2.3 which shows the traditional trade-off curves between customer service and inventory level for the FPp and MTS approaches. This chart suggests that - all other things being equal – FPp requires a lower level of inventory than MTS to provide the same service level. This is supported by a number of FPp cases. For example Swaminathan and Tayur (1998) studied the final assembly of IBM RS6000 machines and provide instances where storing inventory in semi-finished forms (called ‘vanilla’ boxes) reduces the inventory requirements while improving response times and providing high levels of customisation.

Closs et al. (1998) suggest that the ‘response based’ supply chain model consistently outperforms the ‘anticipatory’ model in terms of customer service (product availability in this case) in conditions of both high and low demand variation. They found that the retailer’s inventory burden was significantly lower in the response-based scenario, and that this inventory reduction was substantial enough to lower system wide inventories through the reduction of demand amplification (Forrester 1958). Inger et al. (1995) supports this work, advocating the introduction of single points of decoupling (Hoekstra and Romme 1992), to reduce demand amplification.

Demand amplification was originally identified by Forrester (1958). Forrester (1958) tracked the delays in a simple business system comprising a factory, a warehouse, a distributor and retailers. When subject to stable demand the system performs smoothly, but variations in customer demand are amplified with each step upstream. Forrester identifies the reason for the ‘demand amplification’ effect as the delayed reaction to demand change, which causes inventory imbalance in the local stocks. Consequently, the replenishment volumes not only support anticipated customer demand but also rebalance of the local inventories.

Forrester (1958) observes that demand amplification increases up the supply chain as you approach the suppliers and results in the pattern of demand up the supply chain bearing little resemblance to the final customer demand. Demand becomes more difficult to predict making satisfactory supply very difficult. Such unreliability of supply is traditionally countered by increased safety stocks, which exacerbates demand amplification making supply even more difficult (Inger et al. 1995). This type of amplification behaviour has been termed the ‘Forrester flywheel effect’ by Houlihan (1987 and 1988), and is illustrated in Figure 2.4.

Huang et al. (2003) describe how demand amplification which results in the amplification of orders and inventory fluctuations upstream is caused by inventory management policies. But Huang et al. (2003) assert that the source of such ‘supply chain dynamics' is 'mainly due to the lack of sharing of production information, including delays and feedback in the decision rules between enterprises in the supply chain'.

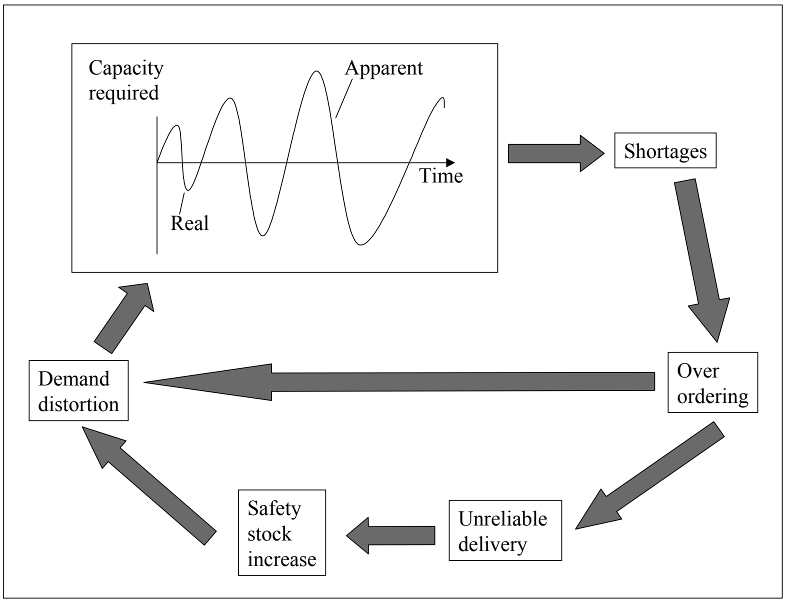



**Figure 2.4: The 'forrester flywheel effect' (Houlihan 1987)**

Lee et al. (1997) have made extensive studies of the distortion of demand information from one end of the supply chain to the other and have termed it 'the Bullwhip Effect'. They identify four major causes of the Bullwhip effect: demand forecast updating, order batching, price fluctuation and rationing and shortage gaming. Johansson et al. (2000) further this work by using a four echelon simulation model (retailer, warehouse, distribution centre and factory) to demonstrate the importance of time buckets to supply chain performance. They conclude that poor synchronisation of time buckets (normally inherent in the MRP system) upstream in the supply chain can result in product shortages down stream and increased inventory costs upstream.

It is argued that FPp reduces demand amplification compared to MTS in two ways. Firstly, the demand variability that the supply chain is subject to is reduced. This is achieved by keeping speculative stocks of the *undifferentiated* generic products rather than the broad range of finished products. At the generic level demand is less variable (Inger et al. 1995, Zinn 1990a). Secondly, FPp links the point of differentiation (or customisation) to the point of sale, by differentiating the product to customer order, thereby eliminating anticipatory finished product stocks in the distribution chain. Christopher (1998) suggests that the ‘tidal wave effect’ experienced by Forrester’s channel participants, in the face of demand variability, can be subdued dramatically by this approach. Further by only customising the products to order many of the causes of the Bullwhip effect (Lee et al. 1997) are reduced.

Postponement is thus widely recognised as an approach that can lead to superior logistics systems or supply chains (Cooper 1993, Jones and Riley 1985, Scott and Westbrook 1991, Shapiro and Heskett 1985). Further, the application of postponement has been observed as a growing trend in manufacturing and distribution by various surveys (CLM 1995, Ahlstrom and Westbrook 1999) and prominent researchers (Christopher 1998, Lampel and Mintzberg 1996).

***Conclusions:*** FPp contributes to achieving the core goals of SCM, or lean logistics, by reducing the inventory level required by the anticipatory approach (MTS) to support a given customer service level. In addition it is argued that FPp reduces demand amplification in the supply chain resulting from the anticipatory approach - MTS. This is achieved by reducing the demand variability that the system is subject to and linking the point of differentiation to the point of sale.

### *2.3.2 Inbound and Outbound Logistics*

The implications for outbound and inbound logistics of applying FPp are addressed in this section, which focuses on the flow of materials into and out of the postponed process.

Van Hoek and Weken (1998) conducted a highly significant study in the automotive industry addressing how modular production can contribute to the integration of inbound and outbound logistics with the manufacturing plant. It was found that modular production allows manufacturers to further involve suppliers and distributors in the supply, assembly and distribution of products. Postponed purchasing is combined with postponed manufacturing as illustrated in Figure 2.5. This increases the integration of supply and assembly on the one hand and assembly and distribution on the other.

According to the definition of FPp a proportion (in fact possibly all) of the components or modules required by the postponed process, will be manufactured in the focal factory and therefore not be subject to inbound logistics at this stage. Other components, supplied by external sources, are subject to inbound logistics. The availability of these components into the postponed process is critical to ensure quoted order lead-time can be achieved. Cox (1989) and Slack (1988) identify that short order lead-times on purchased items support mix flexibility, as required by the postponed process. If the purchased items can be ordered within the order lead-time offered to customers they do not constrain the flexibility of the Master Production Schedule (MPS) as they can be purchased to customer order (Browne et al. 1996).

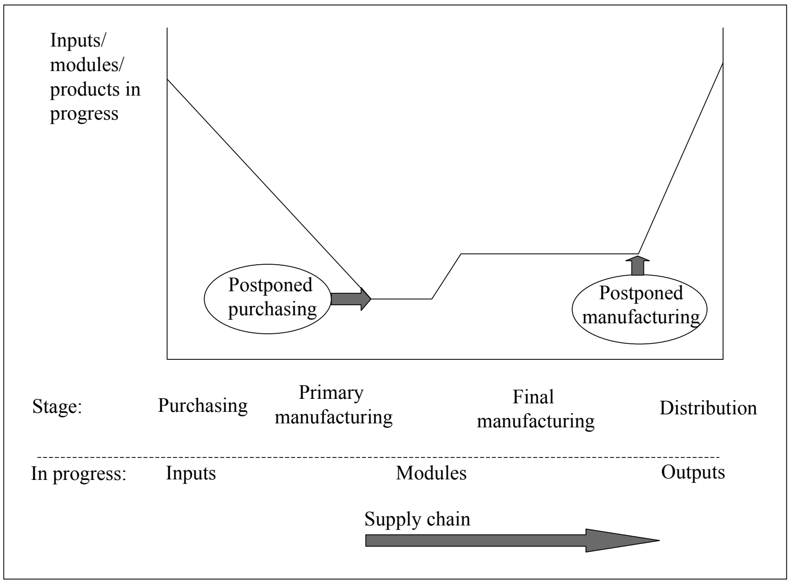



**Figure 2.5: Stage wise evolution through postponed purchasing and postponed manufacturing (van Hoek and Weken 1998a)**

Van Hoek and Weken (1998) revealed 'postponed purchasing' of many modules subject to inbound logistics. This leaves suppliers in charge and possession of goods until they are actually needed in the assembly process, normally the postponed process. This is similar to Vendor Managed Inventory (VMI), which involves the vendors assuming total responsibility for the entire 'replenishment-of-stocks' process (Peck 1998). The vendor manages the 'goods receivable' inventory dedicated to one customer, at a location convenient for the customer, which may be on their site.

Like 'postponed purchasing' VMI supports FPp by allowing the postponement of goods receipt until the factory (applying FPp) are in receipt of a customer order. Whether 'postponed purchasing' or VMI is applied to inbound logistics, inventory is still the *responsibility* of the factory and it is in their interest to ensure inventory is minimised to reduce risk of obsolescence from new product transitions (Magretta, 1998). Therefore the accuracy of the forecasts for components, which is used to determine order quantities, is still critical.

Alternatively JIT may be a suitable approach to inbound logistics for modules or components sourced externally. Schonberger's (1982) seventh lesson in simplicity, 'travel light and make numerous trips' encourages:

- more frequent deliveries in smaller quantities,
- rationalised supplier bases and
- location of suppliers nearby as described by van Hoek and Weken (1998).

This results in reduced safety stocks of modules and components. Swenseth and Buffa (1991) argue for great care in drastically reducing safety stocks. They point out that as cycle time is reduced under JIT conditions, the effect of *inbound variability* is very important, because of the increased delivery frequencies and lower shipping weights. They further claim that some means to reduce the variability of vendor delivery performance should be implemented in conjunction with JIT. JIT is also inappropriate if demand for the components, or modules, is *variable* as it requires a level schedule (Slack et al. 1998, Vollman et al. 1992). For instance demand for 'option' modules is likely to be significantly more variable than that for 'common' modules (Browne et al. 1996). Therefore JIT is not viable and higher safety stocks may be required.

Van Hoek and Weken (1998a and 1998b) noted that the incidence of doorstep JIT suppliers being opened next to the manufacturer appears to be growing. However, they observe that these suppliers may not be (physically) close enough to the manufacturer. In fact the new first tier suppliers may be called 'zero level or zero tier' suppliers. Here the suppliers move into the factory to conduct assembly of modules - they are no longer an outside supplier but become integral partners that control a significant amount of the value adding process (Van Hoek and Weken 1998).

The outbound logistical implications of applying FPp originate from the requirement to deliver-to-order a broad range of products to a possibly fragmented market, in an efficient manner, whilst providing required customer service. Van Hoek and Weken's (1998) automotive manufacturing case studies reveal that product modularity enables the rapid and easy final modification to customer order, of the vehicle, in the distribution channel, termed 'postponed manufacturing'. Further, van Hoek (1998) and van Hoek et al. (1996 and 1998) recently carried out a major study into the application of 'postponed manufacturing' in European supply chains. This study is concerned with postponement as a method for achieving a balance between globalisation (global efficiency) and localisation (local responsiveness) as addressed by Craig and Douglas (1996). The study found that the implementation of 'postponed manufacturing' requires the reconfiguration and design of the outbound logistics or downstream supply chain. The starting point in the change process was found to have a significant effect on the supply chain reconfiguration process. For example the European companies tended to start with nation-based supply chains, and the change process focussed on centralising operations in order to enhance global efficiency.

***Conclusions:*** Those components, supplied by external sources into the postponed processes, are subject to inbound logistics. The availability of these components into the postponed process is critical to ensure quoted order lead-time can be achieved. Accordingly a number of tactics for inbound logistics are identified including purchase on a very short lead-time; postponed purchasing; VMI; and JIT supply. The suitability of these approaches depends on the component demand variability, volume demand and the suppliers lead-times. Outbound logistics is not of great significance to this study and therefore is only briefly addressed.

### *2.3.3 Information Systems and Technology*

Literature addressing the logistical implications for the information systems and technologies of applying FPp are reviewed here.

Management information systems are concerned with the movement, manipulation, and presentation of information for use in the management of organisations (Slack et al. 1998). This is distinct from information technology, which is concerned with the configuration of the physical system, the information processing devices, such as computers, and the telecommunications, such as Electronic Data Interchange (EDI) (Slack et al. 1998).

A response based system, like that required to support FPp, substitutes information for inventory enabling the entire system to react more readily to changes in demand than the anticipatory system (Closs et al. 1998). In a response based system each supply chain entity must be able and willing to share critical, timely information (for example sharing customer order information with suppliers) in order for the benefits of improved co-ordination and efficiency to be realised (Lee et al. 1997). Scott and Westbrook (1991) claim that JIT supplies will typically not be viable without the regular and reliable issue of sales forecasts on which the suppliers can base their plans. This implies that sales forecasts, for modules and components supplied to the postponed process, must be shared with the respective suppliers.

Massey Ferguson failed to share final assembly schedules with their supplier. This coupled with cumbersome forecasting and planning systems seriously impaired their responsiveness. In 1986 Massey-Ferguson in the UK took six weeks to convert a sales forecast into a supplier schedule, but within the factory they planned production on actual customer orders only three to four weeks ahead. Massey Ferguson failed to make the final assembly schedule available to the suppliers (Harrison and Voss, 1990)

Stalk and Hout (1990) warn of the dangers of slow information lead-time - 'the underlying problem here is that once information ages, it loses value…old data causes amplifications, delay and overhead'. Forrester (1958) identifies the reason for the 'demand amplification' effect as the delayed reaction to demand change, which can be caused by old information. Naylor et al. (1999), describing the integration of lean and agile paradigms, identifies 'Information Enriched' supply chains (Mason-Jones and Towill 1997) where each member receives the marketplace information (commonly consumer demand) directly. They claim this increases transparency, reduces distortions and reduces lead-times.

Droge et al. (1995) conducted a sample survey of Council of Logistics Management members, and found that FPp is associated with a more intensive formal control system. Firms applying FPp are pressured to operate JIT delivery systems that require tight control of costs and service levels both *to* customers and *from* suppliers. Droge et al. (1995) concludes by stating that all requisites of this operating environment could be met by an information system that: (1) has built-in formal control mechanisms that renders obsolete information processing middle managers; and 2) seamlessly connects the firm to suppliers and customers (through EDI for example).

Van Hoek (1998) and van Hoek et al. (1996 and 1998) note that advances in information technology are an important enabling factor for companies wishing to implement postponement strategies. Especially as they can reduce transaction costs associated with the control of goods in supply chains, and enable rapid response to customer orders. Modern information technology can now 'orchestrate' the revolution of operations from a 'push' to a 'pull' system required for postponement (CLM 1995).

Closs et al. (1998) claims that investment in information technology 'makes the response-based system viable'. In a study comprising a survey of companies based in Holland from the electronic, automotive, food and clothing industries Van Hoek (1998c) found a positive correlation between the external application of Information and Communication Technology (ICT) and the application of FPp. This indicates that using ICT to link production upstream with suppliers, and downstream with logistics service suppliers and customers, supports FPp.

Electronic Data Interchange (EDI), which is the use of data exchange networks to transmit information relating to inter-operation trade (Slack et al. 1998) is a prominent example of ICT. EDI can be used to transmit orders, make payments, communicate stock availability amongst other information. In this way lead-times are reduced through the shortened transaction times of a paperless system (Scott and Westbrook 1991, Slack et al. 1998). In a study conducted by Naylor et al. (1999) the application of FPp in an electronics products supply chain, advocated linking suppliers and customers via EDI such that all orders are communicated this way.

Advancing the idea of EDI connections with customers one step further, Dell Computer Corporation sells directly to individual customers through the Internet and call centres allowing the customer to configure their requirements themselves (Magretta, 1998). Similarly, Van Hoek and Weken (1998) report in a case study on the SMART car (manufactured by Micro Compact Car AG) that mutli-media systems are used to enable clients to ‘build’ their car in the showroom.

It appears that the Internet provides an opportunity for the application of FPp, since purchasing on the Internet is, like mail order – it always involves an order lead-time. Whether the manufacturer uses the order lead-time to finish the goods, as in the case of Dell Computer Corporation (Magretta 1998), or simply transports the goods ex-stock is not of interest to the consumer as long as they receive the customer service they expect.

***Conclusions:*** A response based information system, like that required to support FPp, substitutes information for inventory enabling the entire system to react more readily to changes in demand than the anticipatory system. This involves supply chain entities sharing critical, timely information in order for the benefits of improved co-ordination and efficiency to be realised. Advances in information and communication technology (ICT) are an important enabling factor for companies wishing to implement FPp. They can reduce transaction costs associated with the control of materials and enable rapid response to customer orders. Electronic Data Interchange (EDI) is a prominent example of ICT and can be used to transmit orders, make payments and communicate stock availability amongst other information.

## 2.4 OPERATIONS MANAGEMENT LITERATURE RELATED TO FORM POSTPONEMENT

This section reviews the OM literature addressing concepts closely related to FPp. The first part reviews literature on non-MTS approaches, of which FPp is an example. The second part considers literature on mass customization, for which FPp is widely recognized as a possible approach. In the final part a more recent body of literature is reviewed which considers the application of postponement as an operations strategy.

### *2.4.1 Non-MTS Approach*

In a review of OM and production literature on non-MTS approaches Amaro et al. (1999) observes that most of this literature classifies the non-MTS companies into three types: ATO, MTO and ETO (see for example Marucheck and McClelland 1986, Hendry and Kingsman 1989, New and Schejczewski 1995, Vollman et al. 1992). These types are defined below:

- ***ATO production***. The final products offered to customers, although presenting some degree of customisation, are produced with (common) standardised parts, which can be assembled into a range of product variants. The receipt of an order initiates the assembly of the component parts which may be purchased or manufactured internally.

- ***MTO production***. Most or all operations necessary to manufacture the product are only performed after receipt of the customer order. Indeed sometimes materials are purchased to customer order. Here the capability for customisation is greater than in ATO.

- ***ETO production***. Products are manufactured to meet a specific customer's needs and so require unique engineering design or significant customisation.

The key distinction between FPp and MTO or ETO is clearly the location of the CODP as previously discussed. When FPp is applied the bulk of manufacturing is conducted speculatively and only the customising processes are performed after receipt of a customer order, thus enabling the responsive supply of a customised product.

Though clearly distinct from ETO and MTO, FPp is not entirely distinct from ATO - there is an overlap between these two categories. Where ATO involves the rapid assembly of components (the bulk of which are manufactured to stock in-house) to provide a wide variety of finished products, then this specific instance of ATO can also be categorised as FPp. However FPp is distinct from ATO in four key respects:

- ***Source of components supplied to the postponed process:*** In ATO all the components required for assembly may be purchased, whereas for FPp the bulk of the components, and particularly the basic or generic product (if it exists), are manufactured in-house.

- ***Nature of the postponed process:*** The postponed process (in FPp) is not confined to assembly in fact it may be any type of transformation process including manufacturing, assembly, configuration, packaging, or labelling as defined in section 2.1.2.

- ***Responsiveness of the postponed process:*** Only a 'short time period' is available for the postponed process – it must be responsive. Whereas this is not necessarily the case for ATO.

- ***Variety of finished products:*** FPp is specifically for the manufacture of products exhibiting high variety whereas ATO may be applied to standard products. 'For example some companies offering high priced standard items for which the demand is intermittent choose to make [or assemble] them only to a customer's order rather than to stock' (Amaro et al. 1999).

Amaro et al. (1999) comment that the ATO, MTO and ETO categories of non MTS approaches are 'very broad and imprecise' and they propose a new taxonomy for non-MTS companies. However, ATO is still only split into two broad categories on the basis of degree of customisation. It is argued that FPp (as defined for this research) is specifically an approach to mass customisation (as discussed in section 2.4.2). Further although FPp overlaps with the ATO category on the whole it is quite distinct from, and more specific than, ATO as it is generally understood.

Amaro et al. (1999) points out that 'the literature addressing the needs of companies which produce in response to customers' orders is astonishingly modest'. Most of the published research in the OM area has tended to treat all companies the same as MTS companies and has neglected the needs of the non-MTS sector. However there are exceptions and over the four years since the Amaro et al. (1999) paper the non-MTS sector appears to have received more attention. This literature is reviewed here using the traditional non-MTS classifications as defined above.

Most of the publications on non-MTS approach address the needs of the traditional MTO sector that manufactures a high variety of customer-specific products not – as is becoming known as MTO – the manufacture of fairly standard products on a MTO basis. The bulk of these publications address issues related to the manufacturing planning and control for MTO for example:

- Marucheck and McClelland (1986) address strategic trade-offs in MTO manufacturing that influence customer service performance. They stress the importance of investment in safety stock and the investment of time, money and support into a Computer Integrated Manufacturing System, which can aid the firm in setting promise dates and in managing production.

- Hendry and Kingsman (1989) identify production planning system requirements for the MTO sector by reviewing existing research on production scheduling, capacity control and the setting of delivery dates. They conclude that more research on production planning systems specifically for the MTO sector is needed. In answer Yeh (2000) develops a customer focussed approach to effective production planning and scheduling in a MTO environment. The approach is described in section 2.5.4.

- Segerstedt (2002) conducts a study of the production and inventory control at ABB Motors (Vastera) and Volvo Wheel Loaders (Eskilstuna) where significant proportions of production are MTO or ATO. The findings are presented in section 2.5.4.

Quite a number of the publications on MTO use mathematical models to address specific planning and control issues, for instance:

- He and Jewkes (2000) and later He et al. (2002) develop algorithms to compute the average total cost per product for a MTO inventory management system. They examine several raw material stock replenishment policies and select the optimal which minimises the average total cost per product.

- Webster (2002) uses a simple mathematical model of a MTO firm and examines policies for adjusting price and capacity in response to periodic and unpredictable shifts in how the market values price and lead-time. The findings are discussed in section 2.5.5 on capacity management.

Muda and Hendry (2002a and 2002b) develop a comprehensive model comprising 14 principles which offer a way to look at the strengths of a company and identify areas for potential improvement. They use Schonberger's (1986, 1996) world-class manufacturing model as a starting point and argue that this model applies to the MTO of relatively standard products rather than the MTO of a high variety of customer specific products (as in the traditional MTO sector).

Very few papers address the specific needs of ETO or ATO. Eloranta (1992) focuses on the problems and potential of one-of-a-kind production of non-standard products (ETO). Here some amount of product design and engineering work are needed for every customer order. The development needs in product design, engineering and also in production system design are emphasised.

Wemmerlov (1984) examines manufacturing planning and control for ATO 'for which parts and sub-assemblies are made according to forecasts while the final assembly of the products is delayed until customer orders are received.' This appears particularly relevant to FPp as Wemmerlov's (1984) understanding of ATO is more specific than normal and is closer to the FPp definition used for this research. However in common with the general understanding of ATO he does not consider ATO to be very responsive offering only a 'medium' order lead-time. He describes how orders are promised on the basis of the availability of components rather than on the basis of a short standard quoted lead-time as for FPp.

The findings from many of these studies that pre-date 1990 have been superseded by text books such as Vollman et al. (1992) reviewed in section 2.5.4.

***Conclusion:*** Much of the published OM research addresses the needs of the MTS companies and neglects the needs of the non-MTS sector. There are exceptions and much of this literature considers the traditional MTO sector. Extraordinarily little research has been conducted on ATO which (like MTO) is considered not to be responsive - orders are promised on the basis of the availability of components and/or capacity rather than on the basis of a short often standard quoted lead-time as for FPp. This thesis contributes to this body of literature by considering the operational issues of FPp, a specific non-MTS approach distinct from the existing categories, ETO, MTO and ATO.

### *2.4.2 Mass Customisation*

The concept of mass customisation was first introduced by Davis (1987) to describe a trend towards the production and distribution of individually customised goods and services for a mass market. Later the term was fully expounded by Pine (1993) based on a survey of US firms, and he specifically defined it as 'a tremendous increase in variety and customisation without a corresponding increase in costs'. More recently, mass customisation has been described as 'providing numerous customer chosen variations on every order with little lead-time or cost penalty' (Ahlstrom and Westbrook 1999). The implied challenge for manufacturers is how to deal with high demand uncertainty at finished item level (which results from the provision of many variants, Inger et al. 1995) whilst ensuring low operational costs are maintained and short, reliable lead times.

Many of the operational challenges of mass customisation originate from the need to manufacture a broad product line. Pine et al. (1993) points out that this can be dangerously expensive. However, a study of over 1,400 business units (Kekre and Srinivasan 1990) indicates that significant market share benefits - and increases in firms profitability - result from broad product lines. This explains the strong motivation for companies to successfully apply mass customisation.

The traditional response to high demand uncertainty, in a MTS environment, is to buffer against them by increasing safety stocks (for example Metters 1993, Newman, et al. 1993, Scott and Westbrook 1991). However, in the case of customised products, it is rarely economically viable to maintain the safety stock levels required to avoid stock-outs. Thus inaccurate sales forecasts are increasingly leading to costly discrepancies between finished stocks and demand. It is argued whatever the degree of customisation the product can only be made or at least finished to order (Amaro et al. 1999, Bennett and Forrester 1994).

At the other extreme MTO is where the manufacturer takes no action (except for the purchase of materials) until an actual customer order is received, therefore more customising options can be offered (for example New and Szwejczewski 1995, Vollman et al. 1992). However, the more activities postponed until after receipt of customer orders the less responsive MTO is compared to MTS (Amaro et al. 1999).

As illustrated there is a trade-off inherent in the MTO and MTS approaches between customisation level and order lead-time. FPp *mitigates* this trade-off by retaining the opportunity to customise whilst minimising the order lead-time (Amaro et al. 1999). FPp has been widely proposed as one approach to mass customisation (for example Bowersox and Closs 1996, Pine 1993, van Hoek 1998, van Hoek et al. 1998, Zinn and Bowersox 1988).

The literature concerning mass customisation is extensive and can be split into that concerned with the strategic impact of mass customisation and that addressing the operational implications or the 'how' of mass customisation. First a selection of the more prominent publications concerned with the strategic impact of mass customisation are reviewed.

A number of publications consider the overall strategies required to achieve mass customisation from both a marketing and organisational perspective (for example Pine et al. 1993 and 1995). Gilmore and Pine (1997) go on to identify four approaches to mass customisation, collaborative, adaptive, cosmetic and transparent. The collaborative approach is most often associated with the term mass customisation, and often involves products where many features are offered in a number of configurations, such as a car. To be precise this is 'mass configuration', rather than mass customisation, as the customer cannot independently specify his requirements, but must *choose* from an array of predefined 'options'. Even though thousands of configurations may be on offer, the customer is still constrained to certain choices. It is argued that FPp is more suited to mass configuration than customisation because the optional components required for a mass configured product are predefined. Therefore in general it is easier to ensure immediate availability of components supplied into the postponed process.

Lampel and Mintzberg (1996) also make a distinction between different types of customisation. They define 'pure customisation' as the only true customisation where the design cannot be created until the customer specification is received. They argue that customisation and standardisation do not define alternative models of strategic action, but rather poles of a continuum of real-world strategies, as illustrated in Figure 2.6.

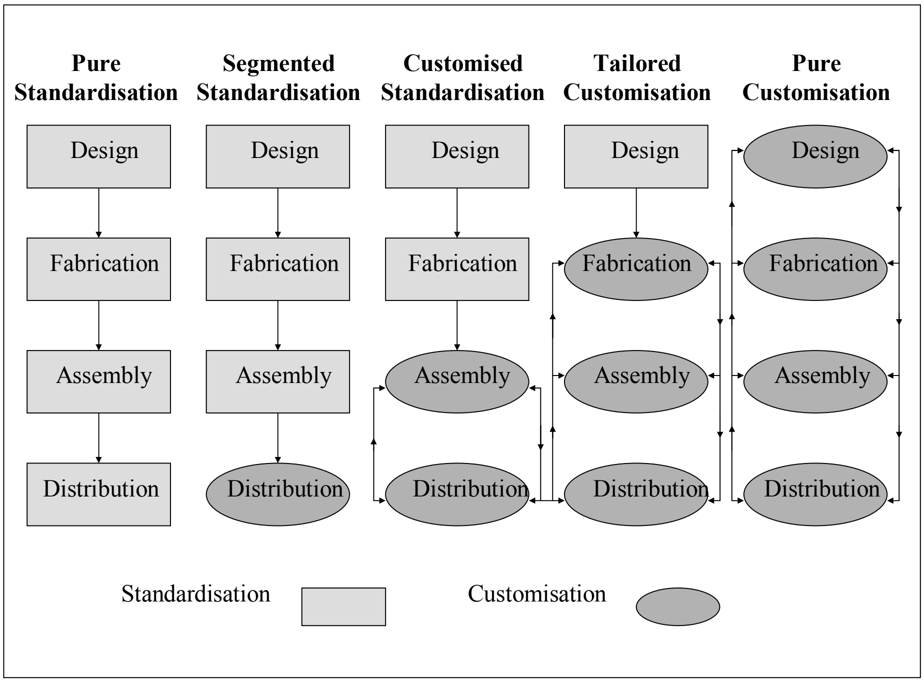



**Figure 2.6: Continuum of Strategies (Lampel and Mintzberg 1996)**

A continuum of five strategies are described from 'pure standardisation' to 'pure customisation'. Each strategy depends on which functions lean to standardisation and which to customisation. Lampel and Mintzberg (1996) argue that the most striking trend has been, not toward 'pure customisation', but toward some middle ground that is called 'customised standardisation'. Under this strategy 'products are made to order from standardised components' – an approach that falls under the umbrella of FPp.

Of the few publications concerned with the operational implications of mass customisation the most prominent are reviewed below and all identify approaches - typically used in FPp applications - as being both popular and effective.

Pine (1993) conducts a survey of US firms to explore the application of mass customisation. Five fundamental methods for achieving mass customisation of products and services are described. He claims that ‘the best method of minimising costs whilst maximising individual customisation is by creating modular components that can be configured into a wide variety of end products’. He goes on to define six different types of modularity which are discussed in section 2.6.2.

Ahlstrom and Westbrook (1999) conducted a survey of UK manufacturing companies concerning the operational implications of mass customisation. Out of seven alternative approaches assembly of core modules was found to be the most used method of achieving customisation. Once again this may be a FPp approach. Various other findings were presented regarding broad operational implications such as the need for improved dialogue between manufacturing and marketing to achieve mass customisation.

Swaminathan (2001) identified three standardisation strategies for mass customisation: part standardisation, process standardisation and procurement standardisation. This was based on six years of detailed analytical and empirical analysis of operational strategies for managing mass customisation with several firms (for example Swaminathan and Tayur 1998 and 1999). A two by two matrix was developed for choosing the appropriate standardisation strategy on the basis of product and process modularity. ‘Process standardisation’ (FPp) where an inventory of semi-finished products is maintained, and customisation postponed until order receipt, was recommended where both the product and process was modular.

***Conclusions:*** The literature concerning mass customisation is extensive, however that concerning the operational implications or the ‘how’ of mass customisation is considerably less. Most of it is concerned with the strategic impact of mass customisation and only a few publications address the operational implications of mass customisation. This thesis contributes to this body of literature by addressing ‘how’ mass customisation can be achieved through the application of FPp.

### 2.4.3 Form Postponement as an Operations Strategy

Recently a small body of literature has emerged in the OM field that deals with postponement and a selection of the papers are reviewed here. It should be noted that although this literature is not concerned with 'logistical postponement' and therefore focuses on FPp the understanding of FPp tends to vary a great deal as previously discussed in section 2.1.1.

Yang and Burns (2003) present a theoretical paper which discusses the implications of postponement for the supply chain. Here postponement is understood in its broadest terms including at one extreme ETO as 'pure postponement' and at the other extreme MTS with distribution to order as 'logistical postponement'. They identify factors from the literature that influence the location of the CODP such as the extent to which manufacturing processes are associated with the customer order. However they point out that 'little attention has been directed to how these factors can be balanced'.

Yang and Burn (2003) observe that with the high degree of uncertainty, it is a natural option to postpone activities. On the other hand, the implementation typically leads to reducing economies of scale and increasing cycle times. They call for more research on 'how various types of postponement are linked to different types of uncertainty'.

Van Mieghem and Dada (1999) show how demand uncertainty influences the strategic capacity investment decision of the firm. They compare different postponement strategies using a two stage decision model where firms make three decisions: capacity investment, inventory quantity and price. However the postponement strategies consist of 'production postponement' which here is MTO and 'price postponement' which is MTS with the price decision postponed. The models are by their own admission very simple but show that: typically capacity investment is made while the demand curve is uncertain; and the relative value of operational postponement techniques seems to increase as the industry becomes more competitive.

Aviv and Federgruen (2001a) perform simulations using a far more complicated analytical model of delayed product differentiation (DPD which is fully discussed in section 2.6.1) which is a design for postponement approach. This model is much closer to FPp as defined for this research however there is no CODP at generic product stage instead it the MTS approach is assumed. The model assumes a common intermediate product is manufactured to stock in the first phase with the differentiating options and features postponed until the second phase and each phase has a lead-time. Production volumes in the first stage are bounded by given capacity limits but there is always sufficient capacity to satisfy demand. The multi-item inventory model is subject to random and *seasonally* fluctuating demand and the findings regarding cost savings (in terms of production, inventory holding, capacity provision) of FPp are as follows:

- as capacity becomes more limited (i.e. capacity utilisation increases) the cost savings of delaying product differentiation (rather than immediately differentiating) reduces. They comment that 'there is less to be saved when capacity is limited because.... the factory must produce at capacity nearly all of the time, regardless of the demand stream'.

- When there is strong seasonality, compared to no seasonality, the cost savings of DPD increases.

- The later the differentiating process is delayed within the total production lead-time the greater the savings from DPD. Differentiating the products after the 1$^{st}$ (2$^{nd}$, 3$^{rd}$, 4$^{th}$) week of a five-week total lead-time reduces costs by 4% (9%, 14%, 20%) when compared to the case where differentiation is not delayed at all. In practice the order lead-time in a FPp application tends to be so short the option of delaying the differentiating process by varying degrees does not exist.

- The less the correlation between end item demands the greater the cost saving due to DPD. The cost savings are least with positively correlated demands, medium with independent demand and greatest with negatively correlated demands, which supports Zinn (1990a) work on risk pooling reviewed in section 2.2.2.

Finally the model used by Aviv and Federgruen (2001a) assumes 'that all demand distribution are perfectly known from the outset' which is not realistic even for MTS.

A further similar model to that described above was developed by Aviv and Federgruen (2001b) to characterise the cost savings of FPp when subject to demand distributions which are *not known* with accuracy but are subject to the 'learning effect'. The 'learning effect' refers to the generation of significantly more accurate forecasts of future demand distributions which allows the differentiation of the products (second phase) to more closely reflect demand. Therefore here the entire production process in forecast driven. They find that the learning effect always results in increased cost savings of DPD.

Ma et al. (2002) model a multi-stage assembly line with multiple products and random demands to explore the dynamics between processing times and component procurement lead-times and their impact on the application of DPD. They conclude that delaying product differentiation by applying component commonality (standardising the product) is usually preferred in the early stages due to lead-time dynamics in the system.

Ernst and Kamrad (2000) use an analytical framework to calculate the costs of four different supply chain structures. Their findings suggest that vertical integration is not desirable – it is better to outsource module manufacture and allow logistics providers to conduct packaging in the distribution chain (distribution FPp). These are interesting results but the framework is limited to postponed packaging and therefore probably consumer products. Further these decisions are dependant on many other variables such as order lead-time, geographical locations of market, factory etc.

***Conclusions:*** A theoretical paper (Yang and Burns 2003) reviewing research on postponement concludes that little is known about its application. Much of the OM literature on FPp uses mathematical or inventory models of postponement applications. Most these models consider delayed product differentiation applied to MTS approaches and therefore are not directly applicable to FPp. With the introduction of a CODP at the generic product stage they could be very useful in understanding some of the operational implications of FPp such as capacity planning. This thesis contributes to this body of literature by addressing 'how' FPp is applied using the case study research design.

# 2.5 OPERATIONAL IMPLICATIONS OF FORM POSTPONEMENT

This section reviews the operations literature relating to the various operational implications of applying FPp. Leagility where agility and leanness are combined in one supply chain is discussed. Manufacturing flexibility in its different forms is considered in particular mix flexibility required for the postponed process. Throughput time and order lead-time are discussed in relation to throughput efficiency. Approaches to manufacturing planning and production scheduling suitable for FPp applications are presented. Capacity planning issues are addressed particularly with respect to the provision of excess capacity at the postponed process. Finally the production variety funnel, central to the conceptual model, of FPp is introduced.

### *2.5.1 Leagility*

A body of literature has emerged that addresses ‘leagility’ where agility and leanness are combined in one supply chain with the strategic use of a decoupling point (Naylor et al. 1999a).

**Table 2.7: Route map for integrating leanness and agility (Naylor et al. 1999b)**

| ***Market Knowledge*** | ***Supply Chain Design*** | ***Optimise for Leanness or Agility*** | ***Results*** | |
|---|---|---|---|---|
| Identify product demand variability<br>Identify product variety<br>Identify point of differentiation<br>Identify lead-time requirements | Integrate supply chain material flow<br>Integrate supply chain information flow<br>Strategic decoupling point<br>Lead-time compression | Eliminate all waste<br>Maximise flexibility without incurring additional waste | Maximise profits with minimum costs and sufficient service to satisfy a level schedule | ***LEAN*** |
| | | Design for total flexibility<br>Minimise waste without restricting flexibility | Maximise profits with maximum service and lowest possible cost to satisfy a volatile market place | ***AGILE*** |

It can be argued in that the two processing stages in a FPp application (generic product manufacture and product customisation) could be labelled with ‘lean manufacture’ and ‘agile supply’ if the demand profile is appropriate. In the case of agility the key point is that the marketplace demands are volatile, whereas in a lean manufacturing environment the demand should be smooth leading to a level schedule as fully described in section 2.5.4.

It should be noted that 'leagility' as defined by Naylor et al. (1999a) and later developed by other researchers (as reviewed below) is applied to supply chains involving a number of 'players': suppliers, factories, distribution warehouses. In the case of FPp (where postponed processes are carried out at the same location as the generic processes) leagility is confined to one factory, however many of the ideas may still apply.

Using the decoupling point (CODP) theory described in section 1.2.3 and a study of an electronics supply chain (Berry 1994) the route map presented in Table 2.7 was constructed by Naylor et al. (1999b). The path to leanness emphasises cost reduction with total waste removal, and the provision of a service suitable for a level schedule. Agility, on the other hand, requires design for total flexibility, providing exactly what the customer requires and only reducing costs when the ability to meet the customer requirements is not impeded. The difference between leanness and agility, in terms of total value provided to the customer, is that *service* is the critical factor for agility whilst *cost* is crucial for leanness (Naylor et al. 1999b). The schematic in Figure 2.7 summarises the implications for FPp *if* leagility can be applied to a FPp application.

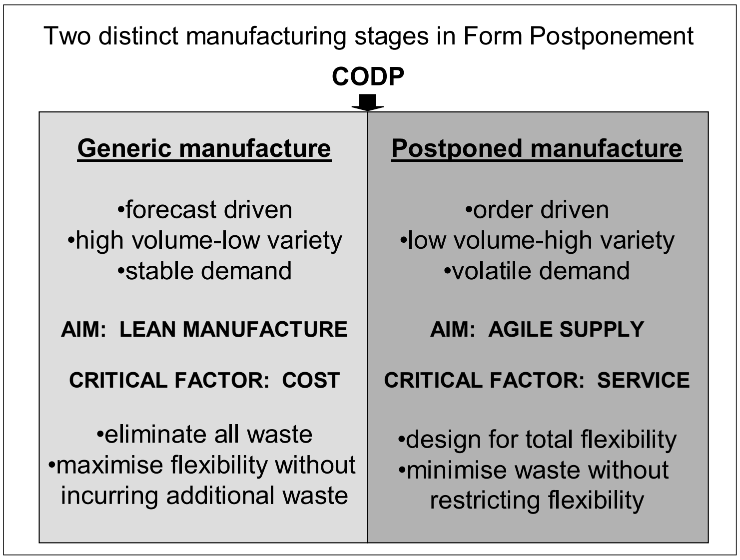



**Figure 2.7: The two distinct manufacturing stages in a FPp application if leaglity (Naylor et al. 1999a) is applied**

Mason-Jones et al. (2000a) claim that the different customer drivers for leanness and agility (cost and service respectively) lead to different capacity calculations. They conclude that the lean processes will tend to operate with little spare capacity – 'as a rule of thumb lean processes tend to base the maximum capacity level on approximately 1.2 times the average demand'. In contrast, an agile process may well be expected to cope with volatile demand swings. Therefore the process may have to be designed so that the maximum capacity level is as high as twice its average demand.

**Table 2.8: Rules to streamline material flow and reduce the Bullwhip Effect (Towill and McCullen 1999).**

| | |
|---|---|
| Rule 1 | Only make products which you can quickly despatch and invoice to customers |
| Rule 2 | Only make in one period those components you need for assembly in the next period |
| Rule 3 | Minimise the material throughput time, i.e. compress all lead-times |
| Rule 4 | Use the shortest planning period, i.e. the smallest run quantity that can be managed efficiently |
| Rule 5 | Only take delivery from suppliers in small batches as and when needed for processing or assembly |
| Rule 6 | Synchronise 'Time Buckets' throughout the chain |
| Rule 7 | Form natural clusters of products and design processes appropriate to each value stream |
| Rule 8 | Eliminate all process uncertainties |
| Rule 9 | Understand document, simplify and only then optimise the supply chain |
| Rule 10 | Streamline and make highly visible all information flows |
| Rule 11 | Use only proven simple but robust Decision Support Systems |
| Rule 12 | The Business Process Target is the seamless supply chain, i.e. all players 'Think and act as one'. |

To aid the application of leagility Towill and McCullen (1999) recommend the removal of system induced uncertainties resulting from the Bullwhip effect or demand amplification (explained in section 2.3.1). Mason-Jones et al. (2000b) argue that the Bullwhip Effect is the same for agile or lean paradigms. However it is argued in section 2.3.1 that in a FPp application the 'agile' postponed process will suffer from almost no demand amplification compared to the 'lean' generic process because it is order-driven rather than stock-driven.

Towill and McCullen (1999) assert that the removal of system-induced uncertainties caused by the Bullwhip effect can be greatly aided by streamlining material flow. This is achievable through the application of a set of tried and tested rules (as shown in Table

2.8). It is argued that for a FPp application these rules are less applicable to the postponed process due to the lack of demand amplification. The first six rules are more relevant to this research on FPp than the latter six as they are more concerned with inventory management and manufacturing planning.

***Conclusion:*** A body of literature has emerged that addresses 'leagility'. It is argued that the two processing stages in a FPp application (generic product manufacture and product customisation) could be labelled with 'lean manufacture' and 'agile supply' if the demand profile is appropriate. The key point is that the demand for the generic products should be smooth leading to a level schedule which is the pre-requisite for elimination of all waste - leaness. Leagility is applied to supply chains involving a number of 'players' - suppliers, factories, distribution warehouses – it is a supply chain strategy. However, FPp in this thesis is confined to one factory, however it is argued that many of the ideas may still apply.

### *2.5.2 Manufacturing flexibility*

Newman et al. (1993) pictures a balance between uncertainty and flexibility (shown in Figure 2.8). He argues that the rewards of reducing uncertainty and increasing flexibility are that buffers (capacity, inventory and lead-time) can be cut.

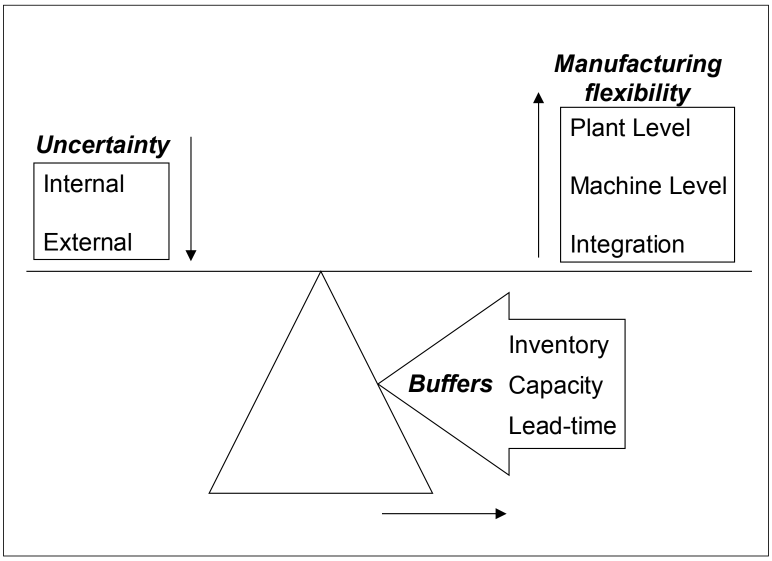



**Figure 2.8: Balance between flexibility and uncertainty (Newman et al. 1993)**

The postponed process in a FPp application is exposed to high demand uncertainty which cannot be reduced. Therefore it is argued that the postponed process should aim to be highly flexible. However it is expected that buffers will still be required if the postponed process is to maintain a high level of responsiveness in the face of uncertain demand (refer to section 2.5.5 for further discussion on buffers). Manufacturing flexibility in it various forms is explored in this section.

Slack's (1987) empirical study on managers' perceptions of manufacturing systems flexibility reveals four types of flexibility: product, mix, volume and delivery, as defined in the Table 2.9. Suarez et al. (1996) supports this work and classifies these flexibility types as 'first order' indicating that they directly effect the competitive position of a firm in its market, and are readily perceived by the customers.

**Table 2.9: Four types of manufacturing flexibility (Slack 1987)**

| ***Flexibility Type*** | ***Definition*** |
|---|---|
| ***Product flexibility*** | The ability to introduce and manufacture novel products, or to modify existing ones |
| ***Mix flexibility*** | The ability to change the range of products being made by the manufacturing system within a given period |
| ***Delivery flexibility*** | The ability to change planned or assumed delivery dates |
| ***Volume flexibility*** | The ability to change the level of aggregated output |

New (1996) and Cox (1989) assert that mix and volume flexibility are the primary types of manufacturing system flexibilities They argue that product and delivery flexibility can be achieved through mix and volume flexibility. In fact Cox (1989) claims that mix flexibility 'includes both changes to existing products and the addition of new ones'. Suarez et al. (1996) empirical findings show that mix flexibility may reduce volume fluctuations, which may *theoretically* reduce the need for volume flexibility. Certainly mix flexibility appears to be the principal type of flexibility required at the postponed process in a FPp application.

There is no consensus in the literature on a definition of mix flexibility. Slack (1987) observes that each of the four first order flexibility types (in Table 2.9) have two dimensions: range and response. Mix range flexibility is 'the range of products the company can produce within a given time period'. Mix response flexibility is 'the time necessary to adjust the mix of products being manufactured'. Both range and response mix flexibility is desirable in the postponed process such that a wide range of products can be produced in a responsive manner. Mix flexibility can be achieved in a number of ways for example: set-up time reduction (Cox 1989, New 1998, Slack 1988), work-in-progress inventory reduction (Cox 1989), and production cycle time reduction (Cox 1989). Further a number of process technology characteristics have been identified that enable high mix flexibility. The extent to which equipment is programmable or is general purpose promotes mix flexibility according to Cox (1989) and Suarez et al. (1996). Slack (1988) adds that equipment with a high range of process capability enables mix flexibility.

New (1998) states any plant can change from one product to another, but the challenge is to achieve this without a loss of efficiency. Upton (1994) supports this view requiring 'little penalty in time, effort, cost or quality performance' in his definition of flexibility. However, as discussed earlier, flexibility (in terms of range and response) is a higher priority than efficiency if the postponed process in a FPp application is to be agile – 'minimise waste without restricting flexibility' (Naylor et al. 1999).

The volume demand variability at generic product (or aggregate) level is always less than that at finished product level (Zinn 1990a). However, there always remains at least some volume demand variability at generic level and in many cases this variability is significant. Therefore volume flexibility, as well as mix flexibility is normally desirable at the postponed process. However it can be argued that demand variability, in terms of both mix and volume, is generally so high at the postponed process that the provision of buffers is essential to maintain responsiveness. It can be further argued that the only buffer available is excess capacity (see section 2.5.5).

***Conclusions:*** The postponed process in a FPp application is exposed to high demand uncertainty which cannot be reduced therefore a high level of manufacturing flexibility is desirable in this process. It can be argued that mix and volume flexibility are desirable in the postponed process, both in terms of range and response. But that demand variability - in terms of both mix and volume - is generally so high at the postponed process that the provision of buffers is essential to maintain responsiveness as discussed in section 2.5.5.

### *2.5.3 Throughput time and Order lead-time*

The 'throughput time' is 'how long the operation takes to obtain the resources, produce and deliver the product' (Slack et al. 1998). This is the same as the 'composite lead-time', which is the difference in time between the final due date for a finished item and the date when the first action must be taken in order to get it made (New 1977). It is important to note that here the throughput time is that for a single company unlike the 'composite manufacturing/procurement lead-time' (New, 1993), which applies to the entire supply chain and is measured from the acquisition of the original raw material.

The order lead-time (referred to by Slack as 'demand time') is 'the time customers have to wait between asking for the product and receiving it' (Slack et al. 1998). Clearly the order lead-time should not be greater than that required by the customer. For a FPp application the location of the CODP in the manufacturing process flow strongly influences the order lead-time achievable since it determines the manufacturing processes that are order driven.

Slack et al. (1998) suggest that the P:D (throughput time to order lead-time) ratio indicates the degree of speculation. Therefore the P:D ratio is an indication of the risks inherent in forecasting. Reducing throughput time (P) is a way of reducing the risks. It is argued that for FPp the risks involved in making to stock the generic product (or modules) are already low because demand is relatively stable at this level. Therefore forecasts are relatively accurate (Zinn 1990a) and the risk of obsolescence is low since they are undifferentiated generic products.

What appears to be more crucial for FPp is reducing the order lead-time, as Fisher (1997) advocates for a responsive supply chain 'invest aggressively in ways to reduce lead-time'. This requires that the manufacturing lead-time for the postponed processes is minimised and the throughput efficiency (New 1993) maximised:

$$\text{Throughput Efficiency} = \frac{\text{Work Content}}{\text{Elapsed Time Taken}}$$

Here 'work content' is the time taken for the value adding activities to be performed on either a batch quantity, order quantity or single item. The elapsed time taken can be measured from release of the factory order to the despatch, or booking into the warehouse, of the finished order. The elapsed time is the time the factory is available to add value and therefore must be measured over the factory's operating hours (New 1993).

It follows that reducing the cost adding, or non-value adding activities, will improve throughput efficiency. Toyota identified seven wastes or non value adding activities: overproduction; waiting; transportation; processing itself; inventory; movement; and making defective products (Shingo 1981, Ohno 1988). Furthermore, the reduction of many of the non-value added activities also improves mix flexibility previously identified as particularly desirable for the postpone process (in section 2.5.2).

Level of postponement is a concept closely related to order lead-time and throughput time. Bucklin (1965) states that operationally, postponement may be measured by the notion of 'delivery time', which is equivalent to 'order lead-time'. He goes on to say for the seller postponement increases, as delivery time lengthens, whereas for the buyer, postponement increases as delivery time shortens. Slack et al. (1998) suggests that the P:D ratio indicates the degree of speculation, conversely the D:P (order lead-time to throughput time) ratio may be a measure of postponement for the manufacturer (seller). However in FPp applications it is desirable to minimise the order lead-time and this reduces the level of postponement according to the D:P ratio. Possibly a better measure would relate to the level of manufacturing processes postponed may be in terms of value added time.

***Conclusion:*** Throughput time is how long the operation takes to obtain the resources, produce and deliver the product. Order lead-time is the time between the customers asking for the product and receiving it. For a FPp application the location of the CODP in the manufacturing process flow strongly influences the order lead-time achievable. The P:D (throughput time to order lead-time) ratio indicates the degree of speculation, and therefore the risks inherent in forecasting. Reducing throughput time (P) is a way of reducing the risks. It is argued that for FPp the risks involved in making to stock the generic product are already low because the volume demand variability at this level is relatively low. What appears to be more crucial for FPp is reducing the order lead-time. This requires that the manufacturing lead-time for the postponed processes is minimised and the throughput efficiency maximised.

### *2.5.4 Manufacturing Planning and Scheduling*

The Master Production Schedule (MPS) is a statement of what the company plans to manufacture. It is the planned build schedule by quantity and date, for top level items, either finished products or high level configurations of material (Vollman et al. 1992 and Brown et al. 1996). The MPS seeks to balance incoming customer orders and forecast requirements with available material and capacity (Brown et al. 1996). An effective master schedule provides the basis for making customer delivery promises, utilising plant capacity effectively, and resolving trade-offs between manufacturing and marketing (Vollman et al. 1992). The diagram in Figure 2.9 shows how the MPS links with the rest of the manufacturing planning and control system (Vollman et al. 1992).

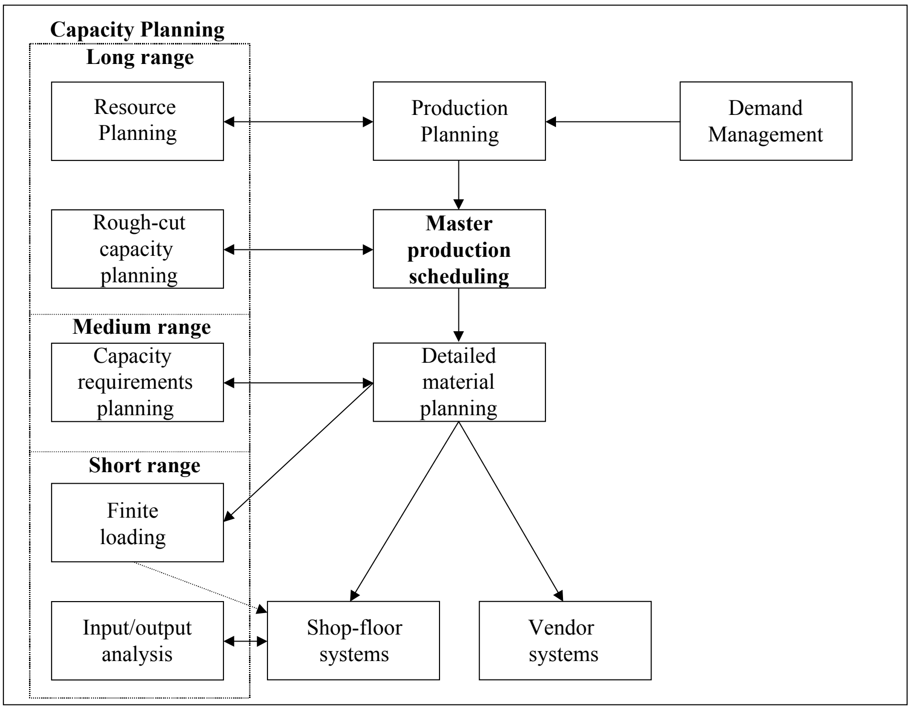



**Figure 2.9: The manufacturing planning and control system (Vollman et al. 1992)**

The MPS drives the Material Requirement Planning (MRP) and is thus the key input into the MRP process. Any errors within it, such as poor forecasts, cannot be compensated for by sophisticated MRP analysis (Brown et al. 1996). This is particularly significant in the case of FPp where order lead-times are short - only the MPS in the near term is dominated by customer orders leaving the MPS heavily dependant on sales forecasts input.

Vollman et al. (1992) claim that the distinction between the three classic types of MPS approaches - MTS, MTO and ATO - is largely based on the production unit used for the MPS. Ling and Widmer (1979) and Proud (1981) suggest the unit is generally at the level in the product structure that provides the greatest flexibility and best control. This is often at the level in the product structure which contains the smallest number of items (Marucheck and McClelland 1986, Brown et al. 1996). For a FPp application this is likely to be at the generic product (or module) level where the CODP is located. Vollman et al. (1992) asserts that the ATO firm is typified by an almost limitless number of possible end item configurations, all assembled to order from combinations of basic components or subassemblies in a similar way to FPp. Vollman et al. (1992) describes how the ATO firm typically does not master production schedule end items but the modules to be assembled which are exploded into component requirements using ‘planning bills of material’.

According to Vollman the bill of material (BOM) is narrowly considered to be an engineering document that specifies the ingredients or subordinate components required to physically make each part number or assembly. The ‘planning BOM’ is any use of ‘BOM approaches’ for planning only. As opposed to the ‘indented BOM’ which is used for building products (Vollman et al. 1992). The ‘modular BOM’ and the ‘super BOM’ are the two principal types of planning BOM (Brown et al. 1996).

The modular BOM is used where the product structure is of the ‘X’ or ‘hour glass type. Each module is defined as a single level BOM, which links components to modules but doesn’t link either components or modules to end items. Effectively it treats the modules as end items (Vollman et al. 1992) and translates the MPS module units into subordinate component requirements. Sales forecasting is aided by the use of super BOMs (defined in the glossary in Appendix 1). Marketing forecast total sales of the product family and make best estimates on the average decimal usage of the ‘options’. The requirements for the modules are calculated by multiplying forecast total sales of the product family by the decimal usage (Browne et al. 1996).

Clearly an MRP system alone cannot manage manufacturing planning and control. Segerstedt (2002) conducts a study at ABB Motors (Vastera) and Volvo Wheel Loaders (Eskilstuna) where significant proportions of production are MTO or ATO. He finds where the number of end items is high, the company ATO or MTO and additions to pure MRP are necessary. He describes the use of planning BOMs (super and modular), normal BOM with ‘adding BOMs’, a MPS planning system with an available-to-promise function and a home made system for modules available-to-promise.

Yeh (2000) develops a customer focussed approach to effective production planning and scheduling in a MTO environment. This may be relevant to the postponed process in FPp because the MTO environment is characterised by small orders placed by a wide variety of customers. Yeh (2000) uses an integrated BOM and routing data structure. This facilitates the creation of production jobs (with varying routing and material requirements) in response to customers’ product specifications. Where the postponed process involves either more than one process or a variety of processes this could be an effective approach.

When considering the manufacturing planning and scheduling implications for FPp applications it is necessary to appreciate the dichotomy in manufacturing (as illustrated in Figure 2.7, section 2.5.1). As described in the introduction chapter the two processing stages either side of the CODP can be appropriately labelled ‘lean manufacture’ and ‘agile supply’. ‘Leanness’ is desirable for generic product manufacture, whereas ‘agility’ is the aim for postponed processing.

Consider first the implications for generic product or module manufacture. The Just In Time (JIT) philosophy founded on eliminating waste from manufacturing (Slack et al. 1998, Vollman et al. 1992 for example) is clearly compatible with leanness. Here leanness means developing a value stream to eliminate all waste in the production system - be it in the form of materials, labour or plant capacity - and to ensure a level schedule (Naylor et al. 1999, Katayma and Bennett 1999). Harrison (1992) states that for JIT implementations ‘manufacture needs to be in small batches with short set-ups and with rapid delivery from one activity to the next’. Thus production can change from one item to another and large batch production avoided (Bennett and Forrester 1994). This is of course very different from the traditional approach to manufacturing items with level demand, which advocates high capacity utilisation through large batch manufacture. This results in high inventories throughout the system and sluggish response flexibility.

However Inger et al. (1995) suggest the decoupling point is where the supply chain moves from forecast-push of material to demand-pull, based on actual customer orders. This would suggest that a push system is appropriate for generic product manufacture. However the work conducted by Slack and Correa (1992) on the flexibilities of push and pull systems suggests that a push system (in this case a conventional MRP system) demonstrates great range flexibility, but at the expense of response flexibility. Ideally high range flexibility is not required for the production of the generic modules therefore an MRP push system is inappropriate. Further push systems are not ideal since they tend to exhibit greater waste than pull systems - the emphasis is on capacity utilisation instead of overall waste minimisation.

The flexibility of a JIT pull system is mainly associated with faster response, as opposed to the ability to produce a wide range of products required for high variety production (Bennett and Forrester 1994, Slack and Correa 1992). This is supported by the nature of the best known JIT examples from firms with high volume repetitive manufacturing methods, such as the classic case of Toyota (Vollman et al. 1992). In fact JIT is not suitable for supplying broad product ranges where demand is highly variable, it requires a level, stable schedule (Slack et al. 1998, Vollman et al. 1992). This implies for FPp applications that where a level capacity plan (as discussed in section 2.5.5) can be established the JIT pull system is suitable.

Agility seeks to cope with demand volatility (Kidd, 1994) and requires design for total flexibility, only reducing costs when the ability to meet the customer requirements is not impeded (Naylor et al., 1999). For the postponed process to be ‘agile’ high mix flexibility is desirable (as discussed in section 2.5.2). This will enable the provision of a broad product range, in a responsive manner, offering short, reliable lead-times (Naylor et al., 1999). Mix flexibility can be achieved in a number of ways which are often methods of reducing waste and therefore achieving leanness – for example set-up reduction. However at the postponed process the guiding principle remains that manufacturing flexibility is a priority over waste reduction.

***Conclusions:*** Ideally the MPS production unit for FPp is the generic products or modules. The MPS drives the MRP and any errors within it, such as poor forecasts, cannot be compensated for by sophisticated MRP analysis. This is particularly significant in the case of FPp where the MPS is dominated by sales forecasts. Planning BOMs such as the 'modular BOM' and the 'super BOM' can be used in conjunction with the MPS. Manufacturing scheduling implications of FPp arise from the dichotomy in manufacturing. Ideally a JIT pull system is suitable for 'lean' generic product manufacture. However where a 'level capacity plan' cannot be established then a MRP push system may be preferable. A demand-pull system based on actual customer orders is necessary for the postponed process which aims to be 'agile' and therefore requires high mix flexibility as discussed in section 2.5.2.

### *2.5.5 Capacity Planning*

Vollman et al. (1992) state that the managerial objective in planning capacity is to ensure the match between capacity available in specific work centres and capacity needed to achieve planned production. Alternatively Slack et al. (1998) state that capacity planning and control is the task of setting the effective capacity of the operation so that it can respond to the demands placed on it, and involves deciding how the operation should react to fluctuations in demand. Clearly providing appropriate capacity is very important to the companies performance (Slack et al. 1998). Insufficient capacity quickly leads to deteriorating delivery performance, escalating work-in-progress inventories, and frustrated manufacturing personnel. On the other hand, excess capacity might be a needless expense that can be reduced (Vollman et al. 1992).

Distinctions are often made between long, medium, and short range capacity planning as shown in Figure 2.9. This thesis is concerned mainly with *long range capacity planning,* which involves resource and rough-cut capacity planning (Vollman et al. 1992). Resource planning involves calculating resource requirements such as labour, floor space and machine hours from the production plan (Vollman et al. 1992), and introducing or deleting major increments of this physical capacity (Slack et al. 1998). Clearly this level of planning can involve new capital expansion, machine tools, warehouse space and so on, which requires a time horizon of months or years.

Rough cut capacity planning involves a relatively quick check on a few *key resources* required to implement the master schedule, in order to ensure that the MPS is feasible from a capacity point of view (Browne et al. 1996). If this reveals that the MPS, as proposed is infeasible then either the MPS must be revised or alternatively more resources must be acquired. The key resources used for capacity planning are those that are constrained and therefore are the first to be expanded when more capacity is required. However as Browne et al. (1996) point out the key constraining resources are not always easy to identify as they often change with product mix.

The product mix, transformed by the postponed process in a FPp application, maybe highly volatile since the demand for each of the finished items is highly variable (Hoekstra and Romme 1992). Required capacity in part depends on product mix (Slack et al. 1998) therefore required capacity is likely to be highly variable even when volume demand at aggregate (generic product) level is stable. However these fluctuations in required capacity can be reduced by increasing mix flexibility as discussed in section 2.5.2. As argued previously as well as high product mix variability there is always at least some aggregate volume demand variability at the postponed process which leads to further variations in required capacity.

The options for capacity planning, in the face of demand fluctuations (product mix or aggregate volume demand) as outlined by Slack et al. (1998) and Vollman et al. (1992) are: level capacity plan, chase demand plan, and demand management. Each of these options is evaluated, with respect to their suitability for the postponed process in a FPp application. The implications for each of the three buffers against demand uncertainty (identified by Newman et al. 1993) – inventory, lead-time and capacity – are considered:

- FPp operates without finished inventory therefore inventory cannot be use as a buffer. This rules out a 'level capacity plan' where according to Slack et al. (1998) the capacity is set at a uniform level throughout the planning period regardless of fluctuations in forecast demand. This approach requires finished inventory to act as a buffer between mismatched supply and demand.

- Similarly, there is little slack in the order lead-time offered since FPp is normally applied to improve the responsiveness of the system (Van Hoek 1998a and 1998b). Therefore 'demand management', where the objective is to transfer customer demand from peak periods to quiet periods so demand is more uniform (Slack et al. 1998), is not a favourable option.

- Capacity (at the postponed process) is probably the only buffer, which is not fundamentally limited in the FPp approach. In this situation Slack et al. (1998) advocates a 'chase demand plan' where capacity is adjusted to reflect the fluctuations in demand. This involves the provision of different quantities of resource such as labour, and equipment in adjacent time periods and can lead to volume flexibility as discussed in section 2.5.2.

Conversely both inventory and lead-time buffers are available for the manufacture of the generic products, however 'demand management' is not an option. A 'level capacity planning' approach would be suitable here. This would depend on the establishment of the correct level of generic product inventory to buffer between the mismatched supply of and demand for the generic products. Where this is possible capacity can be set at a uniform level and a JIT pull system is more likely to be viable as described in section 2.5.4.

In addition to using the 'chase demand' approach to capacity planning for the postponed process strategic 'excess capacity' is desirable, to enable production to respond to the high demand fluctuations. Plossl (1985) points out that excess capacity is essential if fast reaction to change is an important competitive requirement as is the case for FPp applications. Steele and Parke-Shields (1993) state that excess capacity creates capacity slack, a strategic weapon that can reduce lead-time and inventory. Similarly many writers (for example South 1985) point out that excess capacity can significantly reduce the level of queue work-in-progress inventory which adversely affects order lead-times. More recently Webster's (2002) analysis using a mathematical model of a MTO firm suggests that maintaining a fixed capacity while using lead-time and/or price to absorb changes in the market results in lower profits particularly when the market is volatile. He finds that from a pure profit maximisation perspective it is best to strive for short and reliable lead-times by adjusting both capacity and price in response to market changes.

Clearly if high throughput efficiency is a strategic aim (as described in section 2.5.3) the likelihood is that capacity utilisation will reduce (as illustrated by the graph in Figure 2.10) and excess capacity will be a necessity.

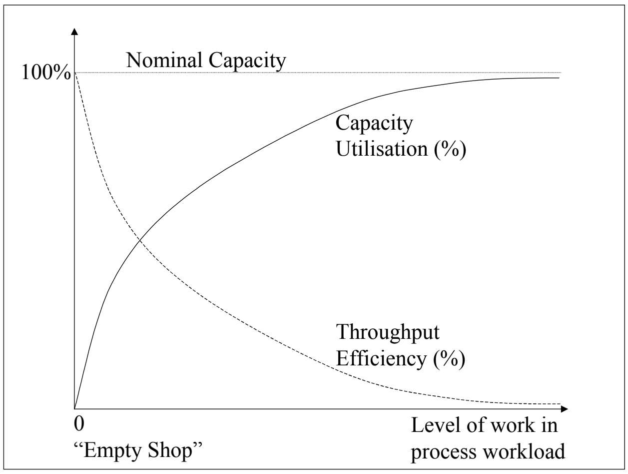



**Figure 2.10: Throughput efficiency, capacity utilisation and lead-time (New 1993)**

South and Hixson (1988) suggest that safety stock requirements are not as great when there is excess capacity available to respond to fluctuations in demand. Mapes (1992) demonstrates that as capacity utilisation approaches 100% substantial increases in safety stock are necessary in order to maintain customer service levels. Clearly, in the case of FPp, where finished safety stocks are absent, if excess capacity is not provided customer service levels will suffer.

***Conclusions:*** This thesis is concerned mainly with long range capacity planning, which involves resource and rough-cut capacity planning. Rough cut capacity planning involves a relatively quick check on a few key resources required to implement the MPS, in order to ensure that the MPS is feasible. Theses key resources normally change with product mix variations, typical of the postponed process. Demand, and therefore required capacity, at the postponed process tends to be highly variable due to volatile product mix and at least some variations in aggregate volume demand. On the basis of available buffers it is argued that a 'level capacity plan' is suitable for generic processes whereas a 'chase demand plan' is more appropriate at postponed processes. The level capacity plan (which supports the application of a JIT pull system) depends on the establishment of the correct level of generic product inventory to buffer between the mismatched supply and demand. In addition to using the 'chase demand' capacity plan for the postponed process, strategic 'excess capacity' is likely to be required. This enables production to respond to the high demand fluctuations in the absence of finished safety stocks and without reducing customer service levels.

### *2.5.6 Production Variety Funnel*

The production variety funnel (PVF) otherwise known as the component flow analysis is a convenient method for describing in graphical terms the number of physically different items that occur at different stages of the manufacturing process (New 1974 and 1977). A PVF for the manufacture of mens underwear is shown in Figure 2.11. Typically the vertical axis represents the number of distinct items, the horizontal axis represents the average process lead-time and the process flow is from left to right.

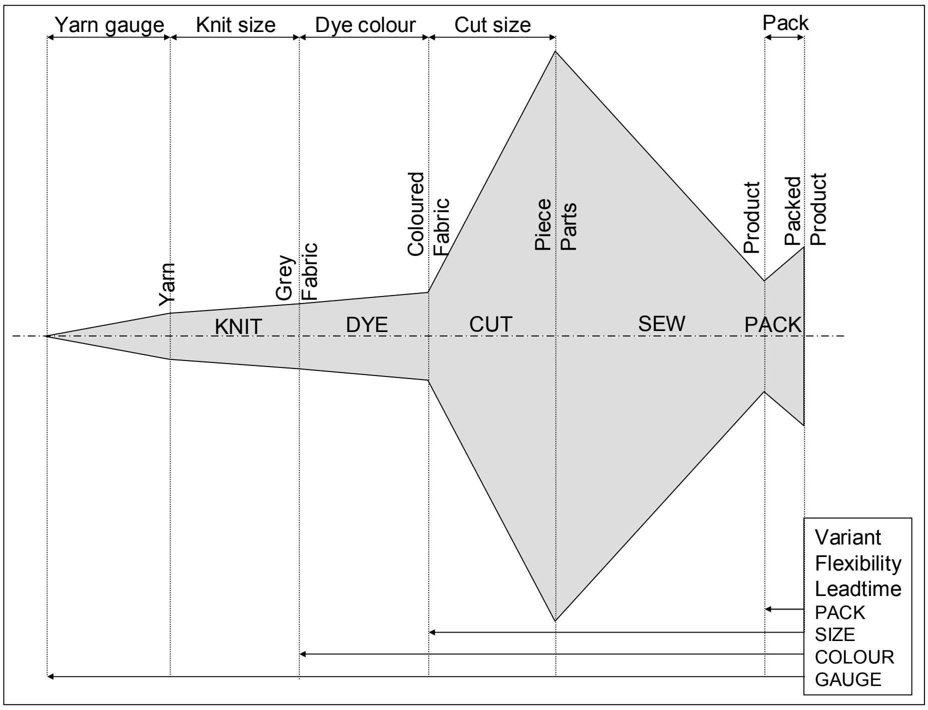



**Figure 2.11: Production Variety Funnel for mens underwear manufacture (New 1993)**

This is distinct from the product structure (or BOM structure) which focuses on the number of distinct components at each BOM level across a product group and does not take into account process lead-times. In the case of product structures the product group is a theoretical selection which may or may not be manufactured in the same production area. The 'shape' of the product structure is normally drawn with the vertical axis representing the different levels of assembly where the top is the finished product (Slack et al. 1998, Browne et al. 1996).

The definition of FPp requires the number of different items to proliferate through the postponed transformation process. In other words it requires the range of generic products (or modules) made to stock to be relatively narrow compared to the range of finished products. Consequently FPp is only viable for product groups displaying certain product structures.

A number of typical product structure 'shapes' can be identified, 'A', 'T', 'V' and 'X' (Slack et al. 1998) as shown in Figure 2.12. The 'A' product structure is typical for MTS, the 'V' for MTO and the 'X' or 'T' type for ATO (Browne et al. 1996).

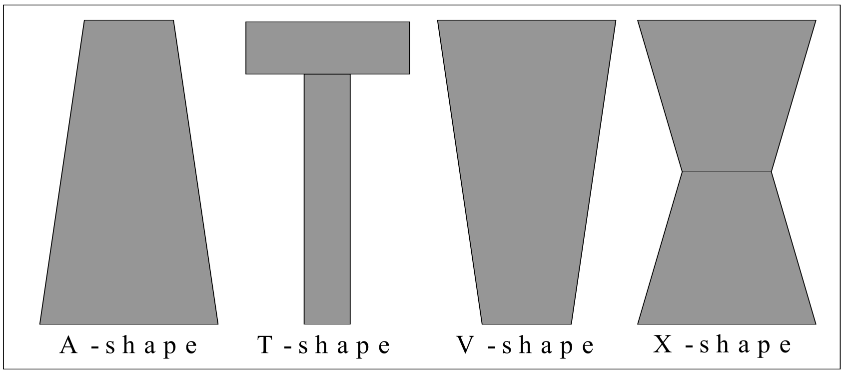



**Figure 2.12: Different shapes of product structure (Slack et al. 1998)**

FPp can only be applied to products with a 'T' or 'X' type product structure since a narrow range of generic product or modules must exist at some mid-way or latter point in the manufacturing process. In a FPp application the CODP is located at the 'neck' in the product structure where a speculative stock of the generic products is maintained. The conceptual model of FPp (presented in section 2.7) developed from the literature review is based on an hypothetical PVF and shows the significance of the CODP location.

***Conclusions:*** The definition of FPp requires the number of different items to proliferate through the postponed transformation process. Therefore FPp can only be applied to products with a 'T' or 'X' type product structure since a narrow range of generic product or modules must exist at some mid-way or latter point in the manufacturing process. In a FPp application the CODP is located at the 'neck' in the product structure where a speculative stock of the generic products is maintained. The conceptual model of FPp is based on an hypothetical PVF which are distinct from product structures in that they consider process lead-times.

## 2.6 ENGINEERING IMPLICATIONS

Engineering literature relating to FPp is reviewed in this section. Delayed product differentiation (DPD), which can be an approach to product and process re-design for FPp, is introduced. The three approaches to DPD are discussed in relation to FPp: product and process modularity; product standardization and component commonality; and manufacturing process re-structuring.

### *2.6.1 Delayed Product Differentiation*

The engineering literature, (Lee and Tang 1997, Garg and Tang 1997, Lee 1996) considers how a product or production process can be re-designed 'so that the point of differentiation is delayed as much as possible'.

Here the 'point of differentiation' is 'the stage after which the products assume their unique identities' or the point where a 'generic product is customised into different end products' using 'specialised components or processes' (Lee and Tang 1997). This approach is given the term 'delayed product differentiation' (DPD). DPD is viewed as an approach to reducing finished goods inventory in a MTS situation – sometimes this involves introducing generic product stocks. The aim of DPD is to maintaining the product in an undifferentiated state for as much of the manufacturing process as possible, therefore it ultimately leads to a standardised product. This is distinct from FPp which is only applicable to customised or highly differentiated products which are stocked in generic form and customised to order. FPp aims to postpone differentiation processes until after the customer orders are received while maintaining responsiveness provided to customers.

Clearly DPD can support FPp where the finished product is not standardised (i.e. remains differentiated) and the remainder of the engineering literature reviewed focuses on this aspect. Lee and Tang (1997) formalise three basic approaches to DPD that some companies have used: standardisation, modular design and process re-structuring. Standardisation refers to ‘using common components or processes’ and is covered in section 2.6.3 on product standardisation. Modular design (discussed in section 2.6.2) refers to ‘decomposing the complete product into sub-modules that can be easily assembled together’ such that ‘the assembly of certain product-specific modules can be delayed’. Finally process re-structuring refers to re-sequencing process steps such that the differentiating processes are performed last (discussed in section 2.6.4).

The costs and benefits of DPD have been explored using inventory modelling with multi-echelon systems. Some research is intended for strategic planning rather than tactical and therefore simplifies the situation dramatically - Lee and Tang (1997) consider a single point of differentiation whereas Garg and Tang (1997) consider products with two points of differentiation. Other research is directed at strategic decisions within a specific company, therefore it has very limited generalisability (Lee and Sasser 1995).

***Conclusion:*** DPD is an approach to product and process re-design such that the point of differentiation is delayed. It reduces finished goods inventory in a MTS situation and can involve the introduction of generic product stocks. The aim of DPD is to maintain the product in an undifferentiated state for as much of the manufacturing process as possible – ultimately this leads to a standardised product. DPD is distinct from FPp which is only applicable to highly differentiated products which are stocked in generic form and customised to order. FPp aims to postpone differentiation processes while maintaining the responsiveness required by customers. Nevertheless DPD can support FPP when the finished product is not standardised (i.e. remains differentiated) and the remainder of the engineering literature reviewed focuses on these aspects.

### *2.6.2 Product and Process Modularity*

The idea of modular products can be traced back to Starr (1965) who identified the emerging ‘consumer’s demand for maximum product variety’. He describes how this can be achieved by designing and manufacturing parts, or modules, which can be combined in numerous ways to produce different product variants. From an engineering perspective product modularity arises from the physical division of a product into independent components, and is frequently stated as a goal of good design practice (Ulrich 1994, Lee 1996, He and Kusiak 1996).

Starr (1965) observed that modular production breaks down the manufacturing process into two main stages, the manufacture of the modules through some transformation process, and the assembly of the modules into a wide range of configurations:

> *'It is the essence of the modular concept to design, develop, and produce those parts (modules) which can be combined in the maximum number of ways.'*

More recently it has been observed that the modules may be inventoried, and the products assembled-to-order, radically reducing the order lead-time, compared to the alternative MTO approach (Ulrich 1994, Feitzinger and Lee 1997). This strategy has been called the 'mushroom approach', because the product variety 'mushrooms' at or near final assembly (Ulrich 1994).

A range of authors present the benefits of modularity most notably that it enables many variants of a product to be constructed from a much smaller set of different modules (Ulrich 1994, Lee 1996, He and Kusiak 1996). Ulrich (1994) and Pine (1993) claim that this variety arises from the ability to use one of several alternative component options to implement a function element of the design. The product can be designed so that physical and functional interfaces between components are the same for all versions of each component (He and Kusiak 1996), such that they are completely interchangeable. Modularity has many other benefits: it offers improved ease of product changes (Baldwin and Clark 1997, Ulrich 1994); and it enables simultaneous design and manufacture of modules such that total lead-time can be shortened (Ulrich 1994, Feitzinger and Lee 1997).

Product modularity also provides companies with the opportunity to rationalise or standardise components (Feitzinger and Lee 1997, Ulrich 1994, He and Kusiak 1996). Ulrich and Tung (1991) argue that it is the 'independence of the components' that allows standardisation and interchangeabilty of components, thus their rationalisation. This results in increased component commonality (Collier 1981, Baker 1985) as discussed in section 2.6.3.

Product modularity is not without its costs. Firstly, modularity assumes a product's functional and physical architecture is static which may be an obstacle to architectural innovation (Ulrich 1994). Secondly, the product performance tends to be compromised by modularity. It is said that the technical performance of a product can always be improved by reducing modularity (Pine 1993, Ulrich 1994), or increasing 'integration' the converse of modularity (Erens and Verhulst 1997). Thirdly, since the physical structure of a modular product is similar to a schematic diagram of its function competitors can more easily reverse engineer the product (Pine 1993, Ulrich 1994).

**Table 2.10: Summary of the six types of modularity identified by Pine (1993)**

| ***Modularity type*** | ***Description*** |
|---|---|
| ***Component-sharing*** | The same component is used across multiple products |
| ***Component-swapping*** | Different components are paired with the same basic product. This is the complement of component sharing and the distinction between the two is a matter of degree at what point does the 'shared component' become the basic product in 'component swapping', e.g. General Motors (Vollman et al. 1992) make a basic J-body car and combine this with a range of different door 'options', cylinder 'options' etc. |
| ***Cut-to-fit*** | One or more of the components is continually variable, e.g. the National Bicycle industrial Company in Japan (Kotha 1995) cuts the bicycle frames to fit the individual customer. |
| ***Mix*** | Uses any of the above modularity types, with the clear distinction that the components are so mixed together that they themselves become something different, e.g. Mexican restaurants create an incredible variety of meals from relatively few components: tortillas, beans various meats, and sauces |
| ***Bus*** | Different components are attached to a standard structure |
| ***Sectional*** | Allows the configuration of any number of different types of components in arbitrary ways as long as each component connects to another at standard interfaces, e.g. Lego building blocks with their locking cylinder interfaces |

Ulrich (1994) states that the degree of modularity depends on:

- the similarity between the physical and functional architecture of the design (Huang and Kusiak 1998) and
- the degree to which the interactions between physical components are critical to the function of the product (Ulrich 1994).

Erens and Verhulst (1997) support this view of modularity stating that ‘in general a modular design is considered to be a design in which a restricted number of functions is allocated to a module’. Ulrich (1994) argues that modularity is a relative property – products cannot be classified as either modular or not but rather exhibit more or less modularity in design. This is a view supported by Baldwin and Clark (1997).

Ulrich (1994) concludes – ‘a completely modular design embodies a one-to-one correspondence between each functional element and physical component, in which every interaction between components is critical to the function of the system’. Here a product can be described functionally by a collection of functional elements linked together by exchanges of signals, material and power - frequently called a schematic description. No products achieve complete modularity, although some electronic products exhibit relatively high modularity.

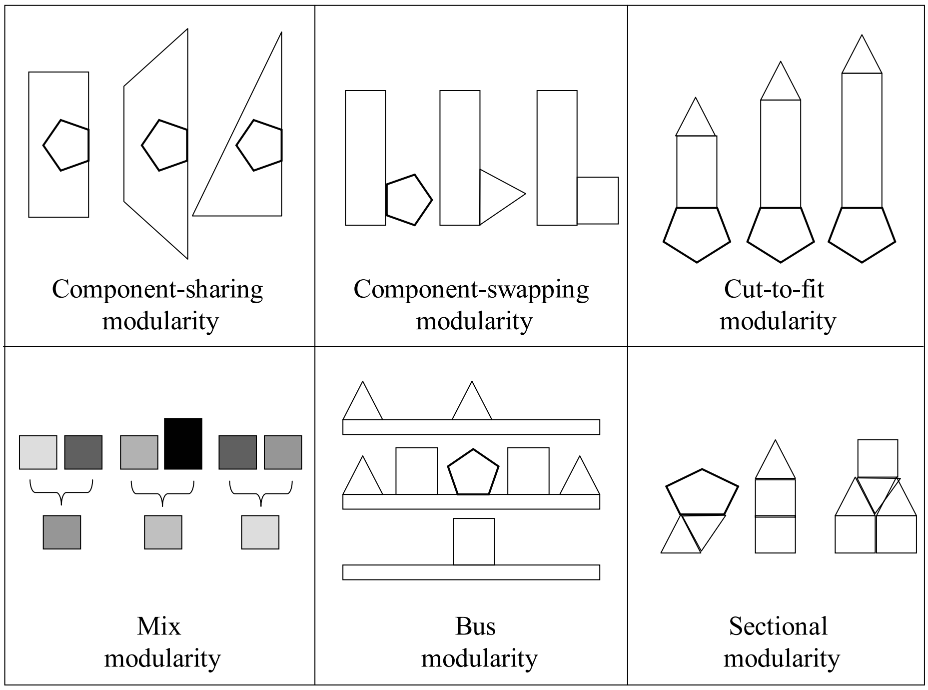



**Figure 2.13: Illustration of the six types of modularity identified by Pine (1993)**

Pine (1993) conducts a study of the different types of modularity and identifies six types (as shown in Figure 2.13 and defined in Table 2.10: Summary of the six types of modularity identified by Pine (1993)) which are very similar to those previously identified by Ulrich and Tung (1991). ‘Component swapping’ is the complement of 'component sharing' and is where different components are paired with the same basic product creating as many products as there are components to swap (Pine 1993). In many cases the distinction between component sharing and component swapping is a matter of degree. Consider Swatch watches: are the basic watch elements a component shared across all the fashion products (component sharing)? Or are the watch parts the basic product and the incredible variety of face styles the components (component swapping)? Component swapping is often associated with the creation of product variety as perceived by the customer (Ulrich and Tung 1991) – highly customised products. In fact Pine (1993) claims that

> *'true individual customisation comes when there are an infinite number of components to be swapped or….at least as many as there are people to buy the product or service'.*

Component sharing on the other hand is

> *'the kind of modularity that never results in true individual customisation…. but allows the low cost production of a great variety of products and services'.*

Very little research relates product modularity to FPp applications. Van Hoek (1998a) and van Hoek et al. (1998) identify product modularity as a characteristic that favours FPp. However the results from van Hoek's cases studies were not conclusive - only two of the four companies applying postponement produced modular products. Van Hoek and Weken (1998) conduct a study in the automotive industry addressing how modular production can contribute to the integration of inbound and outbound logistics with the manufacturing plant (as reviewed in section 2.3.2).

***Conclusion:*** Product modularity arises from the physical division of a product into independent components which can be combined in numerous ways to produce different variations of the product. Modules can be manufactured to stock and then assembled-to-order called the 'mushroom approach' or FPp. The degree of modularity depends on: the similarity between the physical and functional architecture of the design; and the degree to which the interactions between physical components are critical to the function of the product. However modularity is a relative property – products cannot be classified as either modular or not but rather exhibit more or less modularity in design. Six types of modularity are identified and a range of authors present the costs and benefits of modularity, however very little research relates product modularity to FPp applications.

### *2.6.3 Product Standardisation and Component Commonality*

Product standardisation arises from the design of a product to maximise the number of constituent components identical across many (or preferably all) of the product variants within a product family. Product standardisation can be an alternative to FPp but still categorised as DPD. For example Hewlett Packard (Feitzinger and Lee 1997, Lee and Sasser 1995, Lee and Tang 1997) adopted the 'standardisation strategy' for their Laser Jet Printer sold into Europe and North America. Formerly two different power supply modules providing 110 volts and 220 volts respectively were required. After the standardisation exercise a single, intelligent power supply module was installed, which automatically adjusted itself to the supply voltage. This could be called a 'Chameleon product' since it changes to suit its environment but is always the same underneath. Another similar example was found in the semiconductor firm Xilinx (Brown et al. 2000). Here the products were programmable, allowing the customers to fully configure the function of the integrated circuit using software. Once again the product had been standardised and therefore was not in anyway differentiated when the customer received it.

When product standardisation is confined to the generic product or modules it can support FPp. Van Hoek (1998a) and van Hoek et al. (1998) suggests that component commonality favours FPp although the results from his cases studies are not conclusive and no measures of commonality are taken. Product standardisation results in component rationalisation and increased component commonality which can be measured by the Degree of Commonality Index. The Degree of Commonality Index, C, derived by Collier (1981) is an analytical index which measures the degree of component part commonality for any set of items, commonly a product family. Given that a BOM is a formal statement of parent-component relationships for product items, a component part can be *any* inventory item, (other than an end item) that goes into higher level items, possibly a sub-assembly.

C is calculated as: $C = N/c$

Where $N$ = the sum of immediate parents for all *distinct* components over a set of end items or product structure levels

$c$ = the total number of *distinct* components in the set of end items or product structure levels

The Degree of Commonality Index is the average number of common parent items per distinct component part (Collier 1981 and 1982). Or put another way the average number of incidences of the distinct component parts across the set of parent items.

In a simulation study Collier (1982) demonstrated that in an MRP environment increasing the degree of commonality reduces the aggregate safety stock levels required to support a given service level. McClain et al. (1984) challenge Colliers results claiming that the simulation was invalid as a test of generality because it only tested special cases where the relationship holds exactly. Baker (1985) claims that the presence of component commonality makes it difficult to determine safety stocks accurately. He demonstrates that commonality destroys the relationship between safety factor and service level.

It is argued that for a FPp application if the degree of component commonality in the generic product or modules is increased the number of Stock Keeping Units (SKUs) is reduced and demand uncertainty pooled (Zinn 1990a). Hence generic or aggregate safety stock levels can be reduced to support a given service level. Lee and Tang (1997) support this view claiming that component commonality increases the flexibility of the aggregate inventories which reduces the risk associated with speculative production of generic products or modules. In addition a greater volume of any one component is used therefore the manufacturing economies of scale are increased and the unit cost reduced (Ulrich 1994, Pine 1993).

Module or component standardisation is not without its costs. Increases in design, and subsequently material costs, often accompany the standardisation of components, since they tend to require excess capability to perform across a wider product range (Ulrich 1994). Ulrich (1994) and Pine (1993) note that products may be perceived by the customer, as excessively similar, so it is advisable to limit standardisation to components that are hidden. Ealey et al. (1996) claim that automotive manufacturers will 'strive for increasing commonality of all components that are *invisible* to the customer'.

***Conclusion:*** Product standardisation is an approach to DPD which involves the maximisation of the number of constituent components identical across many of the product variants. When it involves the standardisation of customising components it represents an alternative to FPp. Alternatively when standardisation is confined to the generic product or modules it supports FPp. Product standardisation leads to increased component commonality which can be measured by the Degree of Commonality Index. This is the average number of common parent items per distinct component part. Many authors document the benefits and costs of component commonality. It is argued that for FPp applications if component commonality in the generic products is increased the number of SKUs is reduced, demand uncertainty pooled and generic safety stock levels reduced.

### *2.6.4 Manufacturing Process Configuration*

The final approach to DPD is the re-configuration of the manufacturing processes. It is argued that where customisation occurs early in manufacturing, it may be necessary to re-sequence the processes to ensure that the product can be customised-to-order within a short 'order lead-time' (Feitzinger and Lee 1997, Lee and Tang 1997). Benetton used this approach in order to apply FPp to their sweater manufacturing operations in Italy (Harvard Business School 1985, Dapiran 1992). Originally the manufacturing process began with dying the wool into a wide variety of colours. Unfortunately the subsequent knitting process was an extremely lengthy one, necessitating that the retailers forecast sales, by colour, 6 months in advance. Naturally these forecasts were notoriously inaccurate resulting in high inventory at the retailers (to buffer against these inaccuracies), forced mark downs and product shortages.

Benetton applied FPp to their most popular lines (which constituted about 20% by volume) by re-sequencing the processes and postponing dying until after the jumpers had been knitted. They were then able to offer a 5 week lead-time on orders by colour such that the retailers' sales forecasts were based largely on actual sales.

Re-sequencing manufacturing processes can be aided by their modularisation. Bennett and Forrester (1994) state that in 'high variety - low volume' manufacture the benefits of modularised product design can be greatly enhanced by also modularising the production processes. He and Kusiak (1998) propose an approach for the design of assembly lines for modular products exhibiting component-swapping modularity (Pine 1993). This approach divides the assembly line into two subassembly lines: the first assembles those modules common to all the product variants in the product family; and the latter conducts those assembly operations involving optional components.

Inventory models are widely used to assist in the design of manufacturing processes for DPD. However these often consider the CODP to be at the finished good stage (MTS) and some level of finished good stock to always be maintained (Garg and Tang 1997 for example). An exception to this was the Lee and Tang (1997) model of the Benetton manufacturing process reversal. They made the general conclusion that for this approach to be effective the postponed process should be a 'high value added process'. It is argued that this is not so and what is crucial is the variety produced by the postponed process which, when high, creates high demand uncertainty. In the Benetton case the benefits of FPp were largely derived from the dying process being based on actual sales information (when postponed) rather than long term sales forecasts.

***Conclusion:*** The final approach to DPD is the re-configuration of the manufacturing processes. It is argued that where customisation occurs early in manufacturing, it may be necessary to re-sequence the processes to ensure that the product can be customised-to-order within a short 'order lead-time'. Benetton used this approach in order to apply FPp to their sweater manufacturing operations in Italy. Re-sequencing manufacturing processes can be aided by their modularisation. Inventory models are widely used to assist in the design of manufacturing processes for DPD. However these often consider the CODP to be at the finished good stage (MTS) and those that don't still suffer from over-simplification which can lead to dubious results.

## 2.7 CONCEPTUAL MODEL OF FORM POSTPONEMENT

The conceptual model shown in Figure 2.14 illustrates FPp from an ideal perspective. The model is based upon a Production Variety Funnel (discussed in section 2.5.6). The vertical axis represents the number of distinct items, and the horizontal axis represents the throughput time. The distribution of the generic items shown may or may not be necessary depending on the geographical location of the postponed process.

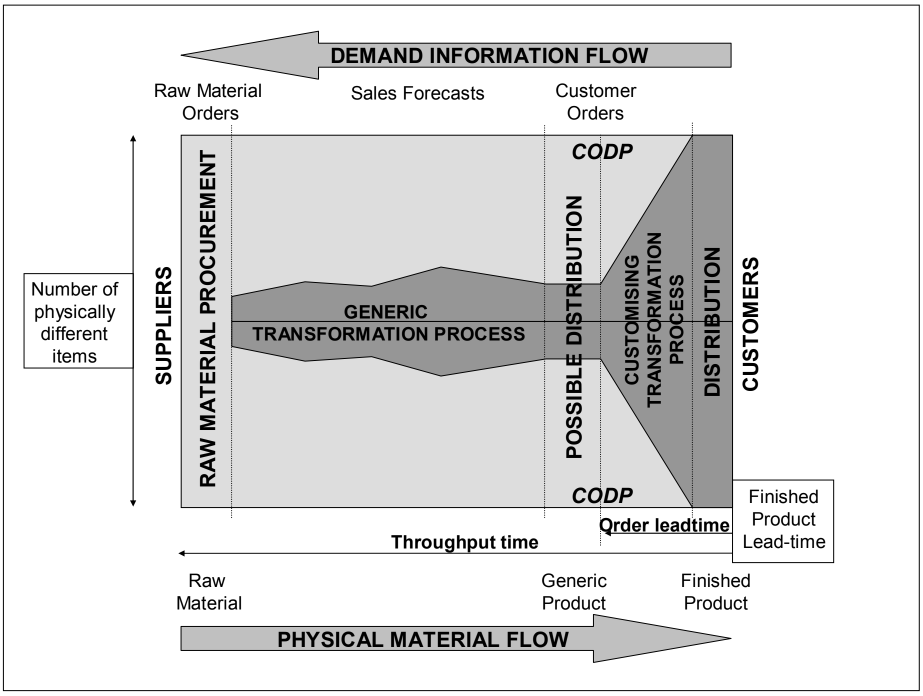



**Figure 2.14: Conceptual model of FPp**

Above and below the PVF are the two kinds of flow associated with supply chains (Scott and Westbrook 1991): a demand information flow “backwards” from the customer and a physical material flow “forwards” to the customer. For an application of FPp the customer orders are available before the final transformation process.

The PVF is hypothetical – and ideal for a FPp application - and shows how a relatively limited range of items stored at the CODP proliferates through the customisation process. This has various operational implications - particularly for product and process design, and for manufacturing planning and control.

The focus of product and process design is to minimise both the stock keeping units (SKUs) at the CODP and the lead-time required for the customising processes - whilst ensuring that the required range of finished products can be supported. The challenge for manufacturing planning and control is to optimise the two contrasting stages of manufacture (pre- and post- CODP). The first stage involves the forecast-driven production of a relatively narrow range of generic items that are subject to relatively stable demand. The second stage is the order-driven production of a broad range of finished products that are each subject to uncertain demand. This implies that the first stage of manufacturing should aim to be 'lean' - where minimising cost, and therefore waste (such as excess capacity) is the critical factor. In contrast the second stage should focus on 'agile supply' - where maximising customer service in terms of short, reliable order lead-times is the key factor (Naylor et al. 1999).

## 2.8 THEORETICAL FRAMEWORK

A theoretical framework (shown in Figure 2.15) was deduced from the previous logistics, OM and engineering research, reviewed in this chapter, on the basis of an ideal FPp application (as illustrated by the conceptual model of FPp). The theoretical framework addresses the research question by illustrating how FPp is applied in terms of a wide range of variables relative to MTS and MTO. This section summarises how this framework was deduced.

Cost models developed by Zinn and Bowersox (1988) and reviewed in section 2.2.2 analysed the impact of various product characteristics on the cost of distribution using FPp where the postponed processes are conducted in the distribution chain. The cost models showed that increases in product variety and demand variability favoured FPp against MTS whereas increases in volume demand at generic level showed no support for FPp. It is argued that these findings, supported by other work (for example, Cooper 1993 and van Hoek 1998a) will apply when the postponed process is brought back into the factory. Further it is considered that low volume demand at end item level will favour FPp compared to MTS while high volume demand at generic level will favour FPp compared to MTO.

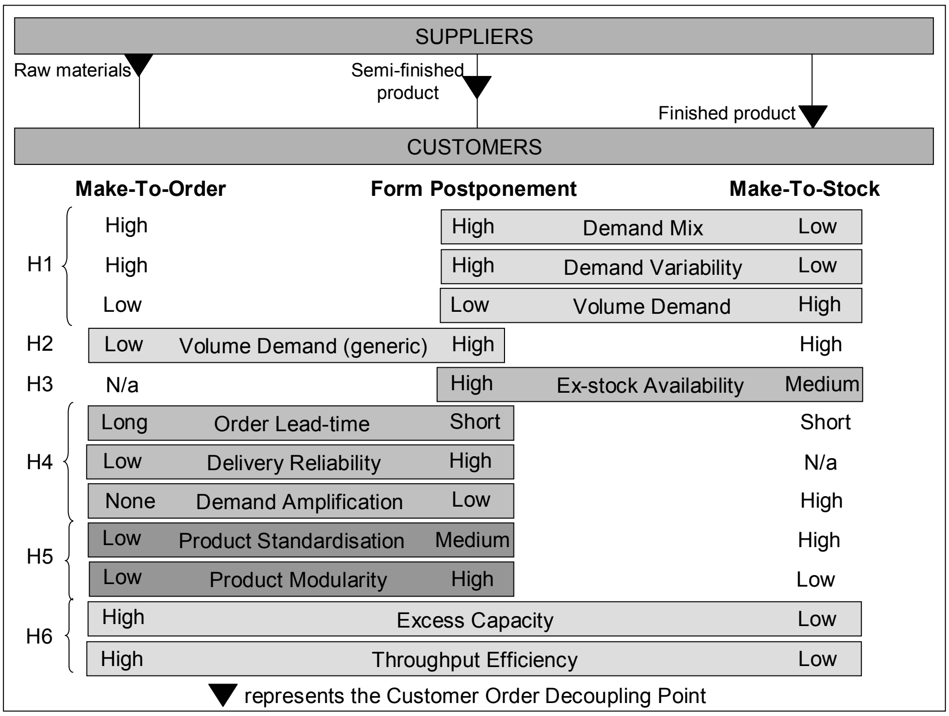



**Figure 2.15: The theoretical framework for the application of FPp.**

In section 2.2.2 it is also discussed how Van Hoek (1998a) and van Hoek et al. (1998) observe that the requirement for short and reliable lead-times favours postponed manufacturing, which in turn improves delivery service compared to MTS. It is argued that while FPp may improve product (or ex-stock) availability, and allow greater product customisation (Amaro et al. 1999) it is unlikely to reduce order lead-time. It is further argued that FPp, compared to MTO, will reduce order lead-time and improve delivery reliability because only the final processing is ‘to-order’ reducing risk of lateness.

Demand amplification is caused by a delayed reaction to demand changes (Forrester 1958) commonly caused by inventory management policies (Huang et al. 2003) as discussed in section 2.3.1. It is argued that FPp reduces demand amplification compared to MTS approaches by reducing the demand variability that the system is subject to, and linking the point of differentiation to the point of sale. Conversely as an alternative to MTO, FPp introduces demand amplification by introducing a speculative generic stock.

In section 2.6.3 it is argued that high levels of standardisation (or component commonality) in the generic products supports FPp by reducing the number of generic product variants which pools demand uncertainty and allows reduction of safety stocks. It is further argued that higher levels of standardisation - not confined to generic modules - favour MTS while lower levels of standardisation involving only components supports MTO. Product modularity is commonly associated with assemble to order as discussed in section 2.6.2 where the modules are inventoried and assembled upon receipt of a customer order (for example Ulrich 1994, Feitzinger and Lee 1997). It is argued therefore that products which are subject to FPp will tend to exhibit a relatively high degree of modularity compared to products which are MTO or MTS.

For a FPp application demand at the postponed process is highly volatile. It is argued in section 2.5.5. that, in this case, strategic ‘excess capacity’ (Steele and Park-Shields 1993) is required to enable production to respond to the high demand fluctuations, in the absence of finished safety stocks, while maintaining responsive supply. It is further argued in section 2.5.3 that the high levels of responsiveness require short postponed manufacturing lead-times and high throughput efficiency. This is loosely illustrate in the theoretical framework by comparing using MTO and MTS to represent the order driven postponed processes and the stock driven generic processes respectively.

## 2.9 CONCLUSION

A working definition of FPp was developed which more closely reflects what manufacturers are actually doing. This definition encapsulates FPp applications where the postponed process is performed at the factory, a warehouse or a retailer. This research is restricted to cases where the postponed process is performed in the factory.

The literature review identified gaps in both OM and logistics knowledge related to how FPp is applied. Three areas of OM research were related to FPp: non-MTS, mass customisation and postponement itself. Much of the published OM research addresses the needs of the MTS companies and neglects the needs of the non-MTS sector. The exceptions tend to address the planning and control systems and consider MTO approaches rather than other non-MTS approaches such as ATO or FPp. Furthermore the non-MTS approaches considered are typically assumed to be unresponsive in contrast to FPp which is a responsive non-MTS approach.

The OM literature concerning mass customisation is extensive. However much of it is concerned with the strategic impact of mass customisation and only a few publications address its operational implications or the ‘how’ of mass customisation. Consequently mass customisation remains largely at the conceptual level and, though the logistical and operational implications are considerable, there has been little practical input from either discipline.

In general the OM literature on FPp uses variable oriented models of delayed product differentiation applied to MTS approaches. Therefore these models are not directly applicable to FPp. With the introduction of a CODP at the generic product stage they could be very useful in understanding some of the operational implications of FPp.

This thesis contributes to OM knowledge related to FPp by addressing the operational implications of FPp - a responsive non-MTS approach to mass customisation. The thesis focuses on the operational implications within the factory including inventory management, product design, production variety, manufacturing and planning and scheduling.

The literature review identified a gap in the logistics knowledge related to FPp. The existing logistics literature in this area considers the conditions under which FPp is justified and the specification of the appropriate FPp strategy. Here FPp is only considered as an alternative strategy to MTS - not to MTO - and the guidelines are restricted to deciding an appropriate postponement strategy rather than its application. In general only FPp applications where the postponed processes are conducted in the distribution chain have so far been considered. As a consequence the postponed processing tends to be relatively simple or trivial. This thesis contributes to this body of literature by considering the application of FPp where the postponed processes are brought back into the factory. Under this scenario substantially more complex processes, than considered in the existing logistical literature, are likely to be capable of postponement.

In addition to identifying gaps in the knowledge related to FPp the literature review identified many of the logistical, operational and engineering implications of applying FPp. This resulted in two main outputs: the conceptual model of FPp (presented in section 2.7); and the theoretical framework (presented in section 2.8). The conceptual model of FPp illustrates product design, process design, and manufacturing planning and control implications for an ideal FPp application. While the theoretical framework addresses the research question by illustrating how FPp is ideally applied in terms of a wide range of variables relative to MTS and MTO. In the next Chapter describing the research methodology the hypotheses are extracted from this theoretical framework.

# CHAPTER THREE

# 3 Research Design Considerations

The literature review in Chapter 2 revealed gaps in our knowledge of how FPp is applied in manufacturing - particularly where both the generic and postponed processes take place in the factory. This is likely to involve the postponement of substantially more complex processes than applications where the postponed processes are conducted in the distribution chain (as considered in the logistics literature).

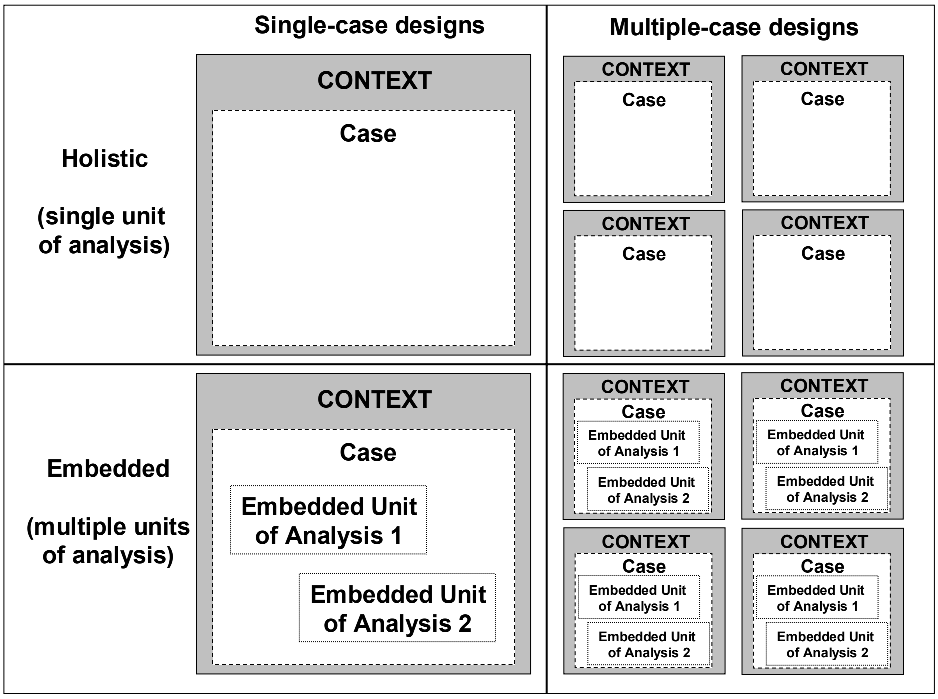



**Figure 3.1: Basic types of designs for case studies (Yin 2003)**

The aim of this research was to understand the reasons for applying FPp in manufacturing and more importantly how it was applied compared to the more established MTO and MTS approaches. The case study approach was selected for the reasons detailed in section 3.2. Two distinct approaches were available for the case study design. The first was to study manufacturing facilities that applied FPp, *'postponers'* and compare them with facilities that did not apply it, *'non-postponers'*. The second option was to study manufacturing facilities where FPp was applied and compare *units of analysis* based around product groups subject to different inventory management policies – FPp, MTO and MTS. Here Yin (2003) describes the unit of analysis as 'subunits' within a single case – effectively cases within a case. The term units of analysis (abbreviated to UoA) will be used to refer to these 'subunits' to bring clarity to the research design.

It was concluded that the design incorporating multiple UoA within a case had a major advantage over the 'postponers' versus 'non-postponers' approach in that it would screen out the contextual differences between factories that are not the subject of this study. For instance it was expected that within a single manufacturing facility the management team, information systems, manufacturing databases, to name but a few aspects, would apply to the whole product range. These contextual aspects would be different between autonomous manufacturing facilities introducing a host of new variables when comparing FPp with non-FPp approaches (i.e. MTO or MTS).

Further, if one restricted the study to manufacturing facilities where at least a proportion of the product range was subject to FPp, one could be assured that the organisation was aware of FPp and had made a deliberate decision as to which products to apply it to. This cannot be said of facilities where FPp had not been applied. At these facilities they may have been totally unaware of the FPp approach, or have some prejudice against it, or simply have never seriously considered it. In conclusion the case study design incorporated multiple cases each with three UoA, as indicated by the fourth quadrant in Figure 3.1.

## 3.1 RESEARCH DESIGN

### *3.1.1 Research Questions and Hypotheses*

The aim of this research was to understand the reasons for applying FPp in manufacturing and more importantly how it was applied compared to the more established MTO and MTS approaches. The research question was:

> ***Why and how is form postponement applied in manufacturing?***

Yin (2003) states that research questions tend not to isolate what you should study and the evidence required. He maintains that only stating hypotheses will focus the research. Consistent with this approach a theoretical framework (shown in Figure 2.15) was deduced in Chapter 2 from previous logistics, OM and engineering research on the basis of an ideal FPp application (as illustrated by the conceptual model of FPp presented in Figure 2.14). The theoretical framework addresses the research question by illustrating how FPp is applied in terms of a wide range of variables relative to MTS and MTO. The hypotheses were extracted from the theoretical framework as indicated down the left side of Figure 2.15. Each hypothesis compares FPp with either MTO or MTS with respect to each of the variables as presented below:

***What is the demand profile of products selected for manufacture under FPp?***

> **H1: Products are selected for manufacture under FPp rather than MTS when they exhibit high demand mix, high demand variability, and low volume demand at finished product level.**
>
> **H2: Products are selected for manufacture under FPp rather than MTO/ETO when they exhibit high volume demand at generic product level.**

***What is the impact on customer service of FPp?***

> **H3: FPp considered as an alternative to MTS increases ex-stock availability.**
>
> **H4: FPp considered as an alternative to MTO/ETO reduces order lead-times and increases delivery reliability but introduces demand amplification**

***What are the product design implications of applying FPp?***

> **H5: Product families subject to FPp will have a higher level of standardisation and modularity than product families subject to MTO/ETO**

***What are the manufacturing planning and scheduling implications of applying FPp?***

> **H6: Capability of the postponed transformation process to respond to high demand variability requires excess capacity and high throughput efficiency**

Much quantitative evidence was gathered on the concepts featuring in the hypotheses, however substantial *qualitative* evidence was also collected via numerous interviews with key personnel (as detailed in section 3.5.2). Here qualitative evidence is ‘words’ and quantitative evidence ‘numbers’ as distinguished by Eisenhardt (1989) and explained in section 3.4.1. The qualitative evidence included contextual data such as the business environment and the reasons for applying FPp. It also incorporated data regarding how FPp was applied such as product selection and manufacturing planning system changes. Further detail is provided on the qualitative data in section 3.1.3.

Eisenhardt (1989) stresses the importance of creating precise and measurable concepts claiming that such concepts are the foundations of powerful theory. Here I am attempting to follow this principle, firstly by defining all the concepts featuring in the hypotheses. Secondly by operationalising the concepts in a way that ensures construct validity (discussed in detail in section 3.4). Nunnally (1978) defines construct validity, amongst other things, as the extent to which an operational measure for a construct reflects all of the construct's observable effects. Therefore operationalisation should involve the exhaustive development of indicators that are directly observable, for each of the concepts.

**Table 3.1: Concepts featuring in the hypotheses and their respective measures including typical sources of evidence.**

| ***Concept*** | ***Measure*** | ***Source of evidence*** |
|---|---|---|
| | ***Internal Variables*** | |
| ***Demand amplification*** | Manufacturing schedules at different processing stages related to customer demand pattern | Customer orders<br>Production schedules |
| ***Ex-stock availability*** | Proportion of initial customer enquiries or orders for which stock is available<br>Forward stock cover | Customer enquiry records<br>Stock records |
| ***Order lead-time*** | Time between order receipt and due date and delivery date (promised and actual) | Customer orders<br>Shipping records |
| ***Delivery Reliability*** | Proportion of orders despatched on time and in full | |
| ***Product modularity*** | Comparison between functional and physical architecture | Interview data<br>Bill of material files |
| ***Product standardisation*** | Degree of commonality index<br>Proportion of common components | |
| ***Excess Capacity*** | Overall Equipment Effectiveness or Capacity Utilisation<br>Process idle time and design capacity | Production records<br>Cycle Times |
| ***Throughput Efficiency*** | Work content as a proportion of elapsed time taken | |
| ***Production Variety Funnel*** | Number of physically different items that occur at each processing stage | Interview data<br>Bill of material files |
| | ***External Variables*** | |
| ***Demand mix*** | Number of product variants demanded | Customer orders |
| ***Demand variability*** | Coefficient of variation of demand | |
| ***Volume Demand*** | Quantity of each item due | |

The respective measures and indicators used, and typical sources of evidence, are summarised in Table 3.1 for each of the concepts or variables featured in the hypotheses. The twelve variables were not intended to form a comprehensive description of the FPp application but to focus a broad based measurement of the UoA to identify the differences between FPp, MTO and MTS. In operationalising the research design some variables were grouped together because they used the same data and were strongly related. Ex-stock availability, order lead-time and delivery reliability were grouped under 'customer service' and the three external demand variables were grouped under 'demand profile'.

### *3.1.2 Internal and External Variables*

Before considering the entire study framework it is appropriate to first define the concepts and measures (in Table 3.1 and defined in the glossary, Appendix 1) which were used to study FPp in each of the three case studies:

***Demand amplification:*** Demand amplification is the effect where variations in customer demand are amplified with each step upstream in the supply chain, such that the pattern of demand upstream bears little resemblance to the final customer demand (Forrester 1958). It results in the amplification of orders and inventory fluctuations upstream and is caused by inventory management policies (Huang et al. 2003), demand forecast updating, order batching, price fluctuation and rationing and shortage gaming (Lee et al. 1997). Demand amplification can be illustrated using a mapping approach described by Bicheno (1998) which can be used in two ways: for a single member of a supply chain and for the complete supply chain. The former approach was used for this study where the chart shows plots of actual customer orders (demand imposed on the manufacturing system), manufacturing orders and orders placed on the next stage of manufacture (the manufacturing process schedule) plotted against time.

***Ex-stock availability:*** is the proportion of initial customer requests (enquiries or orders) for which the correct product is available ex-stock in sufficient quantities (New and Szwejczewski 1995). It only applies to MTS and FPp, not MTO where no product stock is normally kept. For MTS it is measured ex-finished goods stock and for FPp it is measured ex-generic stock. Stock levels, in terms of forward cover, combined with delivery reliability were sometimes used as indicators of ex-stock availability.

***Order lead-time:*** is the time between the customer ordering the product and receiving it. The promised and actual order lead-times were measured from the receipt of the customer order to the respective delivery dates. In the absence of delivery-to-the-customer dates the ex-works dates were used with the proviso that transit times were not taken into account.

***Delivery reliability:*** is the ability of the operating facility to meet the agreed terms of delivery with respect to the product type, the quantity ordered and the due date (Hoekstra and Romme 1992). Delivery reliability was measured by comparing actual delivery dates and quantities with promised due dates and quantities, normally detailed on the customer order. In the absence of delivery-to-the-customer dates the actual and promised ex-works dates were compared. The delivery reliability measure culminated in the calculation of: the proportion of orders delivered on or before the last committed delivery date (on time); and the proportion of orders where the quantity and type delivered were correct to the order (in full). These measures were combined to give the on time in full (OTIF) measure.

***Product Modularity:*** arises from the physical division of a product into independent components (Ulrich 1994, Lee 1996) which can be combined in numerous ways to produce different variations of the product (Starr 1965, Pine 1993). According to Ulrich (1994) the degree of product modularity depends on the similarity between the physical and functional architecture of the design and the degree to which the interactions between physical components are critical to the function of the product. He argues that modularity is a *relative* property – products cannot be classified as either modular or not but rather exhibit more or less modularity in design. He concludes that a completely modular design embodies a one-to-one correspondence between each functional element and physical component, in which every interaction between components is critical to the function of the system. Here a product can be described functionally by a collection of functional elements linked together by exchanges of signals, material and power - frequently called a schematic description (Ulrich and Seering 1989).

***Product standardisation:*** arises from the design of a product such that the maximum number of constituent components are identical across many (preferably all) of the product variants within a product group. It results in component rationalisation, or commonality, which can be indicated by two measures: the proportion of components common to all variants in the product group and the degree of commonality index. The latter is the average number of common parent items per distinct component part (Collier 1981 and 1982). Or put another way the average number of incidences of the distinct component parts across the parent items. It is calculated by dividing the sum of immediate parents for all *distinct* components by the total number of *distinct* components over a set of end items or product structure levels.

The higher the degree of commonality index the greater the overall level of component commonality. However, viewing this measure in isolation is not sufficient it must be considered in relation to its upper bound. The upper bound is when all distinct components are common across all the end items (Collier 1982) and is therefore equal to the number of end items. Accordingly the commonality index was interpreted as a percentage of the number of end items in the product group.

***Excess Capacity:*** is the percentage amount that available capacity exceeds demand. It can be argued that the manifestation of excess capacity is dependant on whether the process is order-driven or stock-driven at a given point in time. In an order-driven situation excess capacity manifests itself as 'process idle time', which is the time when the process could be producing but is idle because the current load does not require this capacity. In a stock-driven situation excess capacity may manifest itself as both process idle time and stock awaiting further processing (or despatch) because load can be created without demand.

Process idle time was used as an indication of excess capacity together with capacity provision or design capacity and capacity utilisation. Two measures of capacity utilisation were used – Overall Equipment Effectiveness (OEE) and the ratio of actual output to design capacity.

OEE was used where capacity was equipment driven which was only in the Thomas Bolton case study (Chapter 4). In this case OEE (the only measure of capacity utilisation used at TB) was measured by the factory routinely during the study period therefore the OEE evidence was readily available in an established database. Further it provided a good indication of excess capacity because the 'planned out' time - equivalent to process idle time - was recorded separately and excluded from the OEE measure (as the OEE definition detailed in the glossary, Appendix 1, dictates). To summarise the main objective of OEE is to quantify the six big losses of capacity, which can be reduced through improved equipment maintenance (Nakajima 1988). OEE is calculated by multiplying three separate factors: availability, performance and quality rate:

- 'Availability' measures downtime losses such as machine breakdowns and set-ups;
- 'performance' measures speed losses caused by minor stoppages and slow running; and
- 'quality rate' measures losses through defects such as scrapped production and re-work.

Actual output as a proportion of design capacity (Slack et al. 1998), which is similar to OEE, was the measure of capacity utilisation used for the other two cases (Brook Crompton and Dewhurst). It was used as an indication of excess capacity – the lower it was the more likely excess capacity existed. Further the relative design capacities of the generic and postponed manufacturing processes were also used to indicate excess capacity – where design capacities were higher excess capacity was more likely to exist. Here design capacity was the theoretical capacity of an operation not usually achieved in practice.

It was argued that using a different measure of capacity utilisation in the TB case did not invalidate the cross-case comparison. The measure was used to indicate the relative excess capacity at the postponed processes compared to the generic processes, not as an absolute measure.

***Throughput Efficiency:*** is the work content as a proportion of total elapsed time taken, where the work content is the time taken for the value adding activities to be performed on an order quantity. The elapsed time is the time the factory was available to add value and therefore must be measured over the factory's operating hours (New 1993). It was measured from release of the factory order to the despatch, or booking into the warehouse, of the finished order.

***Production Variety Funnel (PVF):*** is a convenient method for describing in graphical terms the number of physically different items that occur at different stages of the manufacturing process. Typically the vertical axis represents the number of distinct items, the horizontal axis represents the average process lead-time and the process flow is from left to right (New 1974 and 1977). The PVF is the only variable listed in Table 3.1 that does not feature in a hypothesis. Instead the PVF was plotted because it was central to the conceptual model of FPp and the shape of the PVF should be strongly related to the inventory management policy. It was a good indicator of whether FPp could have been applied to other products (currently MTO or MTS) and whether the CODP could have been better located for the FPp application.

***Demand profile:*** included three external variables: ***demand mix, demand variability*** and ***volume demand***. Demand was quantified from customer order due dates and quantities. Demand mix was the number of variants subject to demand. Demand variability is the changes in demand over a given sequence of time buckets (Battacharya et al., 1995). It can be measured using the coefficient of variation (CV) - the ratio of standard deviation to average. Volume demand is the quantity of a given item demanded.

### *3.1.3 Case Study Framework*

The internal and external variables described in the previous section (and shown in Table 3.1) effectively described the outcome of applying FPp in terms of a wide range of measures such as demand amplification, customer service, and excess capacity. Mapped onto Pettigrew's (1990 and 1992) 'meta level' analytical framework these measures constituted the 'outcome variables' as shown in Figure 3.2 and are highly quantitative measures.

Pettigrew's framework enables change to be studied in different environments without theory limitations in comparative case study research. There are three primary considerations: context, content and outcome variables. First is the 'context' in which the long term change process takes place. Second is the 'content' of the parcel of interventions that comprise the 'change' (the 'what'). Content also describes the *process* by which the change is delivered (the 'how') where process is 'a sequence of events that describes how things change over time'. Pettigrew (1992) argues that in the conduct of strategy process research the content (the 'what') and the process (the 'how') should be regarded as inseparable. The third consideration is the 'outcome variables', which describe what is being explained and must be clearly identified and measurable.

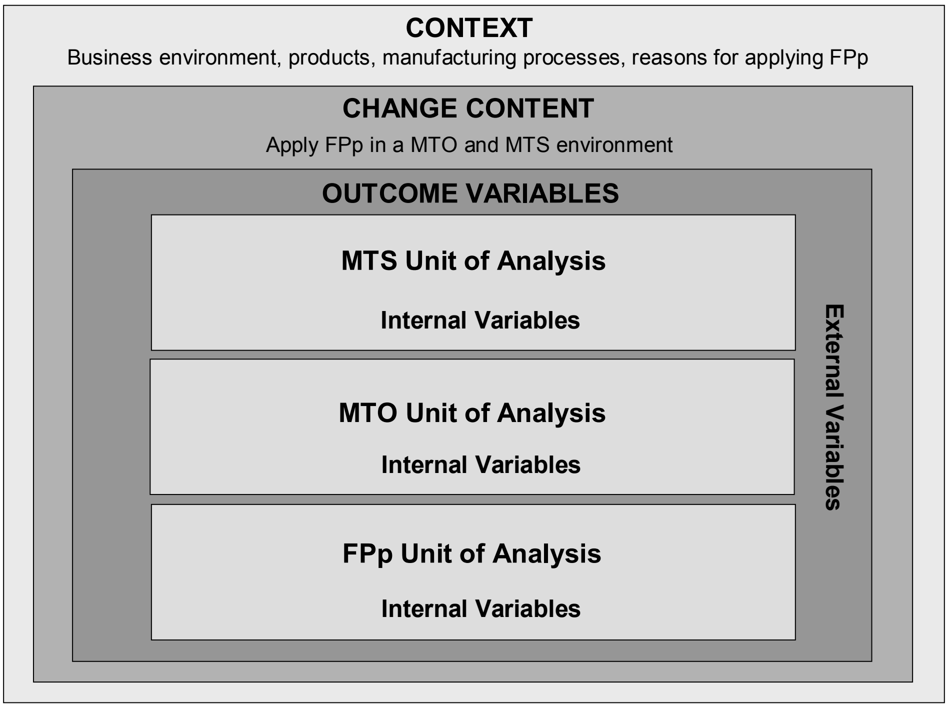



**Figure 3.2: Meta level framework for the case studies.**

According to Pettigrew's framework in order to understand how FPp is applied it is necessary to study the 'context' in which it is applied and the 'change content' required to apply it. Both the study of the 'context' and 'change content' involved the collection of qualitative data via many different interviews. The most relevant contextual features identified for a FPp application were: the business environment of the manufacturing facility; the type of product subject to FPp; and the types of manufacturing processes required to make them. A further important contextual feature was the reason, or motivation, for the application of FPp.

The 'change content' was the application of FPp in a previously MTO and MTS environment. The operations which may be subject to change were identified from the literature review. Clearly products (or customers) are selected to be manufactured using the FPp approach and possibly the product design and manufacturing processes are changed. Inventory management in terms of order processing and the subsequent control of stocks *must* be changed to apply FPp. Also inherent in the inventory management approach is the Customer Order Decoupling Point (CODP) which is naturally relocated when FPp is applied. Manufacturing planning and scheduling in terms of the process from orders being present on the Master Production Schedule to jobs being scheduled through the operations was also likely to be changed. To complete the picture qualitative evidence was collected on problems encountered with the FPp application and potential improvements.

Evidence was gathered on all the operational features and variables in the study framework for each of the three case studies. Where possible the same type of evidence was used, for example the same measures were used to indicate the variables. The remainder of this Chapter fully details the research design with regard to data collection and analysis.

### *3.1.4 Units of Analyses and the Study Boundaries*

As described the case study design incorporated multiple cases each incorporating three UoA to enable FPp to be compared with MTO and MTS in the same context. Each UoA was based around a *product group* subject to a particular *inventory management policy* and included the associated customer orders due for delivery within a *certain time frame*. Three distinct dimensions highlighted in italics defined the UoA. Clearly in practice identifying such UoAs was not easy. For example in the case of the pilot study no one product group was exclusively manufactured according to one inventory management policy.

The product groups selected for the three UoAs were as similar as possible in terms of general design and manufacturing processes. This ensured that the comparison between the different inventory management policies in terms of the various outcome variables (or measures) screened out product specific factors. Thus, the explanation regarding how FPp was applied and its impact on performance was more easily discernible through comparison.

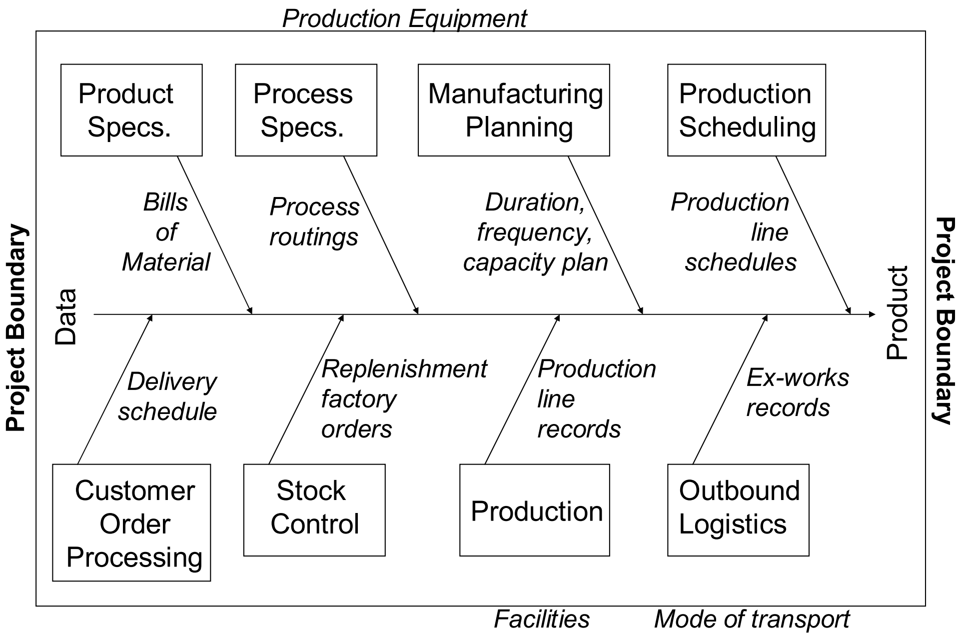



**Figure 3.3: The scope of the case studies in terms of the business processes**

All three studies were conducted retrospectively - not in real time. Therefore the time period, spanned by each UoA, was prior to the commencement of the study (but always within the previous 18 months). Retrospective studies enabled longer study durations than a real time study would have allowed. Further the completeness or reliability of the data was not harmed by their retrospective nature as discussed under data collection (section 3.5.2). Care was taken to ensure that, in each case study, all three UoA spanned the same time period. This was an important consideration because the within-case analysis required the comparison of the three UoA.

In this research design, defining the UoA is not sufficient to determine the boundary of the research. According to Harrison (2002) ‘a problem in conducting case study research is where to draw the line’. He observes that ‘in practice, the boundary will often define itself reasonably well if you have clarified your research design’. This was true of this research which, like Harrison’s (2002) study at Rover Cars, focussed on the processes which convert data into products as illustrated by the fishbone diagram in Figure 3.3. This diagram shows which processes fell within the boundary of the study and therefore were included in each case. Also, it shows any associated processes, which were ruled out of the study. For instance process specifications in terms of processing rate and routings were ruled in the study but the design of the processing equipment was ruled out.

## 3.2 JUSTIFICATION FOR CASE STUDY APPROACH

At the heart of the justification for case based research is the relevance versus validity argument. Swamidass (1991) analysed OM papers published in eight relevant journals. He concluded that in 85% of these papers, none field-based operations research, or management science methods (including computer simulation experiments) had been applied to OM problems to derive prescriptive solutions. He concludes that 'practitioners consider most OM research to be irrelevant, narrow, trivial and unrealistic'. He is not alone in this view. Meredith et al. (1989) reviewed the shortcomings of OM research identified by a number of critics. He concluded that 'OM research has failed to be integrative, is less sophisticated in its research methodologies than the other functional fields of business, and is, by and large, not very useful to operations managers and practitioners'. Moreover, the need for more descriptive, empirically based research is argued by a number of authors (Flynne et al. 1990, Mintzberg 1979, Meredith 1993).

This body of literature reviewing past OM research forms a theme which is commonly expressed by researchers who are interested in improving the practical significance of OM research. However there are concerns about the rigour of empirically based more descriptive research. Daft and Lewin (1990) highlight one such concern saying it 'requires comprehensive understanding of a specific situation that is often not generalisable to other settings'. Ragin (1987) has expressed similar views in relation to research on sociology. He draws distinctions between variable oriented research and case-orientated research. On the one hand variable oriented research is based on the application of multivariate statistical techniques, delivers broad generalisations and seeks average influence across a variety. But conclusions tend to be vague and abstract and have an 'unreal quality'. In contrast case-orientated research is based on the application of multiple methods which seek to account for all deviating cases creating a rich dialogue between theory and evidence. However here there are few general conclusions which tend to be specific to the relatively few cases studied. Clearly whichever approach taken there are shortcomings that must be acknowledged.

Variable oriented OM research includes computer simulation modelling and large sample survey based research which has become the favoured method for much influential research in OM. For example Ahlstrom and Westbrook's (1999) survey to explore operational issues surrounding mass customisation and New and Schejczewski's (1995) study on the relationship between performance measurement and the focussed factory using the best factory award survey data.

It is true that large sample surveys compared to small sample case studies gain on validity in terms of statistical significance and generalisability however they lose on relevance. Lawler (1985) states:

> *'Organisations are studied by researchers that never see them! The result is rather antiseptic descriptions of organisations and the development of theories from these. To a degree broad brush is the enemy of research that influences practice'*

Starbuck (1995) continues on this theme and raises some poignant issues regarding large sample statistical studies:

- A true statement about a population may not apply to any individual case: statistically significant but with no meaning
- Generalising impedes true understanding: properties shared by all organisations are superficial obvious or unimportant
- Following averages can mislead us into thinking how organisations are the same, when what matters is how they are different

The key strength of the case study approach is that it does not isolate the phenomenon under study from the context in which it exists. On the contrary it allows the phenomenon to be studied in relation to its context. This is a consideration that is largely ignored by more variable oriented approaches, such as surveys or modelling, and results in many of the identified weaknesses of this approach. Ragin (1987) states that case-orientated research is based on the application of multiple methods which seek to account for all deviating cases, and therefore creates a rich dialogue between theory and evidence. This is particularly significant for the proposed research concerning the application of FPp because this body of research is still small - especially that which considers the operational implications. It is said that in an area such as this where the theoretical base is weak 'field based approaches are the best ways to find out about the issues, describe the problems, discover solutions and generally ground our theory in the complex, messy world of real organisations' (McCutcheon and Meredith 1993).

Eisenhardt (1989) notes that one advantage of field-based research techniques such as case studies is that operational measures are more likely to be measurable and usable in hypothesis testing because of their grounded nature. This makes case study research especially valuable in developing, testing and refining operational measures for constructs. This is a necessary precursor to theory testing and therefore particularly important for my research.

The issue of using operational measures for constructs is also one which disqualifies the survey approach for this research. A postal survey in particular would be an inappropriate approach because many of the concepts, such as FPp itself and modularity, are not generally understood and open to misinterpretation. An administered survey would also have proved insufficient because many of the variables are too involved to understand without close scrutiny of company records, special data collection exercises and prolonged enquiry with informants. Many of the measures for example demand amplification and variability are unlikely to be measured by a manufacturing facility and therefore require a special data collection exercise. While other measures such as delivery reliability are likely to be measured by the factory, but are *unlikely* to be administered in the same way and with the rigour required. Most importantly the artificial disaggregation of variables into questions, necessary for a survey, denies the dynamic and holistic nature of operations systems. As a result surveys fail to address the interconnections involved. These problems are compounded by the relative remoteness of the researcher who may only pay occasional visits to participating companies.

Voss et al. (2002) argue that 'case research has consistently been one of the most powerful research methods in OM, particularly in the development of new theory'. Harrison (2002) states that 'case study research is of particular value where the theory base is weak and the environment under study is messy' as is the case in the research of FPp. Finally Yin (2003) has provided guidelines on the appropriate research strategy depending on:

- the form of the research question;
- whether the researcher has control of, or access to, the actual behavioural events under study;
- the degree of focus on contemporary, as opposed to historical, events.

My research involves a how and why question and therefore is explanatory in nature. Such questions deal with operational links which need to be traced over time rather than mere frequencies or incidences. Therefore the survey approach is not suitable. FPp was a phenomenon that the researcher had no control over, but access to, because it is a contemporary phenomena. Therefore experiments and histories were eliminated from the possible research strategies and the case study approach emerged once again as the most suitable strategy.

Finally I acknowledge that there are different approaches to case studies. Action research is one approach that at first glance appeared to have great potential for studying how FPp was applied. However this approach was rejected because of numerous envisaged practical difficulties. Firstly, the identification of a manufacturing operation that was planning to implement FPp in the near future, and was willing to participate in the research. Secondly, the application of FPp involves a change in strategy and sometimes the redesign of the product and manufacturing processes, and therefore is a lengthy process. Further, the risk of FPp not being fully implemented was high which would have prevented the outcome of a FPp application being researched. The view was held that it was more practical and equally meaningful to study a company that was already in the business of applying FPp.

## 3.3 RESEARCH PERSPECTIVE

### *3.3.1 Philosophical position*

Ontology is the claims that an approach to social research makes about the nature of social reality i.e. what exists (Blaikie 1993). This has implications for epistemology, which is the criteria that determines what is knowledge, as opposed to beliefs. There are many different views of ontology and epistemology but to explain the philosophical view adopted for this research it will suffice to explain the two extreme views.

**Table 3.2: The key features of the positivist and phenomenological paradigms (Easterby-Smith et al. 1991)**

| | ***Positivist paradigm*** | ***Phenomenological paradigm*** |
|---|---|---|
| ***Basic Beliefs:*** | ***The world is external and objective*** | The world is socially constructed and subjective |
| | ***Observer is independent*** | Observer is part of what is observed |
| | Science is value-free | ***Science is driven by human interests*** |
| ***Researcher should:*** | ***Focus on facts*** | Focus on meanings |
| | ***Look for causality and fundamental laws*** | ***Try to understand what is happening*** |
| | Reduce phenomena to simplest elements | ***Look at the totality of the situation*** |
| | ***Formulate hypothesise and test them*** | ***Develop ideas from induction from data*** |
| ***Preferred methods include:*** | ***Operationalising concepts so that they can be measured*** | ***Using multiple methods to establish different views of phenomena*** |
| | Taking large samples | ***Small samples investigated in depth or over time*** |

Positivism assumes that the social world exists externally and that its properties should be measured through objective methods (Easterby-Smith et al. 1991). Similarly Morgan and Smircich (1980) present objectivism as a view where reality is assumed to be a concrete structure. A major epistemological implication of positivism is that knowledge is only of significance if it is based on observations of the external reality in the form of objective measures.

Phenomenology, on the other hand, assumes that reality is socially constructed and given meaning by people (Husserl 1946). Subjectivism is a similar ontological view where reality is a projection of human imagination (Morgan and Smircich 1980). This view assumes that human action arises from the sense that people make of different situations, rather than a direct response from different stimuli (Easterby-Smith et al., 1991). Therefore in this case the task of the social scientist should not be to gather facts and measure how often certain patterns occur (as is the approach under positivism), but to appreciate the different constructions and meanings that people place upon the experience.

Easterby-Smith et al. (1991) provide a useful comparison between positivism and phenomenology with respect to: the basic beliefs of the researcher; the research strategy; and the preferred research methods (as summarised in Table 3.2). The paradigm assumed for this research is identified by the shaded boxes.

My own beliefs are basically positivist - not surprising when one considers my background in engineering. My natural inclination to the positivist view undoubtedly influenced my choice of research topics but more significantly the research focus, strategy and methods. The main research question was 'how is FPp applied in manufacturing?' One of the choices I made was to study the 'hard' issues such as the manufacturing planning systems, delivery reliability and capacity utilisation - rather than issues related to human constructs such as decision processes, personal motivations and change management.

However, the approach to the research deviated from the pure positivist approach in a number of aspects as illustrated in Table 3.2 where the position of this research is indicated by the shaded boxes. In fact no fewer than six aspects commonly associated with the phenomenological paradigm were adopted. This was largely a result of the selection of the case-oriented approach in preference to the variable oriented approach.

Easterby-Smith et al. (1991) point out that this situation is not uncommon:

> *'although the basic beliefs associated with the two paradigms are quite incompatible, when one comes down to the actual research methods the differences are by no means clear cut and distinct. Increasingly there is a move amongst management researchers to develop methods and approaches which provide a middle ground and some bridging between the two extreme view points.'*

Although the study focused very much on the facts and causality it also sought to understand overall how FPp was applied in terms of the changes to various operations. In fact rather than reducing the phenomenon to its simplest elements it was studied in its totality in its real life context enabling causality to be better understood. Hypotheses were developed from the theory and were tested against observations as expected under the positivist approach. However observations were also made inducing generalisations, and new ideas, as discussed in more detail in the following section on research strategy. Concepts were operationalised so they could be measured but also multiple methods were deployed under the case study approach such as structured interviews, documentary evidence and observations. Finally, only a small sample of manufacturing facilities were studied as dictated by the in-depth case study approach.

*Natural* ——— *Artificial*

*Rational* ——— *Existential*

| *Approach to Knowledge Generation* | *Direct Observation of Object Reality* | *People's Perceptions of Object Reality* | *Artificial Reconstruction of Object Reality* |
|---|---|---|---|
| Axiomatic | | | • Reason/Logic Theorems<br>• Normative/ Descriptive Modelling |
| Logical Positivist/Empiricist | • Field Studies<br>• Field Experiments | • Structured Interviewing<br>• Survey Research | • Prototyping<br>• Physical Modelling<br>• Laboratory Experimentation<br>• Simulation |
| Interpretative | • Action Research<br>• Case Studies | • Historical Analysis<br>• Delphi/Expert Panel<br>• Intensive Interviewing<br>• Introspective Reflection | • Conceptual Modelling |

**Figure 3.4: Framework for research methods (Meredith et al. 1989)**

Another useful framework which helps to position this research in relation to its philosophical basis, and other approaches, is one adapted for OM by Meredith et al. (1989) after Mitroff and Mason (1982) shown in Figure 3.4.

Two dimensions shape the framework and define the philosophical basis for research activity. Firstly there is the rational/existential dimension (y-axis) which relates to the philosophical approach taken to generating knowledge – that is the epistemological viewpoint of the researcher. At the 'rational pole' the research tends to be deductive, formally structured and concerned with coherence with 'laws'. At the 'existential pole' the research process is more inductive, more subjective and concerned with correspondence with the real world rather than existing laws. Secondly, there is the natural/artificial dimension (the x-axis) which concerns the source and kind of information used in the research. At the 'natural pole' concrete, objective data is used in a study of the 'real' phenomena which is more concerned with validity and less with reliability. At the 'artificial pole' the research is concerned with artificial reconstructions of reality which involve highly abstracted and simplified models – more concerned with reliability and less with validity.

As Yin (2003) points out 'case study enquiry relies on multiple sources of evidence, with data needing to converge in a triangulating fashion' where 'sources of evidence' refers to different methods such as structured interviews, documentary evidence etc. Harrison (2002) points out that 'case study research is actually an envelope for several possible research methods – more accurately referred to as a research strategy'. Accordingly most case study research would not fit neatly into one of the quadrants in framework developed by Meredith et al. (1989). This research involved multiple case studies (unlike the single case study assumed by Meredith et al. 1989) and incorporated multiple methods including field studies of multiple sites. Also structured interviews which were mainly fact gathering, but included more subjective data were heavily utilised. Therefore this case study research bridges four different quadrants as indicated in Figure 3.4.

Meredith et al. (1989) maintain that 'the critical issue is the balance between reliability and validity'. He continues that 'current research in OM has tended to lie in the rational-artificial quadrant' and thereby has been highly reliable and efficient but demonstrated low levels of external validity and 'utility'. This research is positioned closer to the natural/existential quadrant and thus provides findings which are, possibly less reliable than previous OM research, but closer to reality and therefore more useful.

### *3.3.2 Research Strategy*

The research strategy is about how the research questions can be answered. As Blaikie (1993) states ‘the crucial issue for the researcher is how to discover, describe, explain and intervene in the phenomena under investigation’. Two of the best known strategies are induction and deduction. Induction moves from observations to the development of general hypothesise, while deduction uses general statements to explain particular instance. It has long been debated how these two approaches relate to each other and Blaikie (1993) asks ‘is it possible to combine these two strategies and thereby capitalise on their strengths and minimise their weaknesses?’

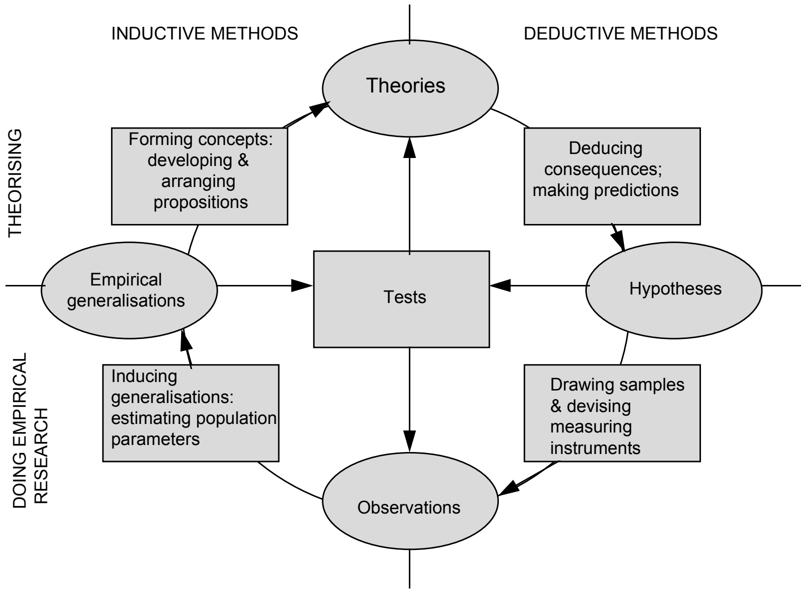



**Figure 3.5: Combining Inductive and Deductive Strategies (Wallace 1971 quoted in Blaikie 1993)**

Wallace’s (1971) cyclical approach, shown in Figure 3.5, combines inductive and deductive methods over the ‘theorising’ and ‘doing empirical research’ activities. Blaikie (1993) notes that although Wallace’s scheme covers *inductive theorising* ‘Wallace appears to have underestimated the complexity of this process which can hardly be called inductive’. Blaikie (1993) concluded that ‘Wallace’s scheme remains within the confines of a Positivist’ ontology which is compatible with this research

This research employed mainly a deductive strategy and an element of induction although *no inductive theorising* was attempted. It is possible to begin research at any point in the cycle and this research began with the deduction of six hypotheses from the theory. The concepts in the hypotheses were translated into measurement procedures and the hypotheses were tested against new observations. The observations were far broader than necessary to test the hypotheses and various empirical generalisations, regarding how FPp was applied, were induced. According to Wallace's (1971) view these empirical generalisation are regarded as summaries of observed uniformities not universal laws.

## 3.4 RIGOUR IN CASE STUDIES

Case studies have traditionally been viewed as a somewhat problematic form of enquiry compared to other empirical methods such as surveys or experiments. A number of concerns are put forward but the most common appears to be a lack of rigour (Yin, 2003, Hartley, 1994). Yin (2003) suggests that too many times, the case study researcher has been sloppy and allowed equivocal evidence or biased views to influence the direction of the findings and conclusions. Supporting this view Swamidass (1991) states: 'an inspection of published field-based empirical articles by OM researchers shows that they are predominantly exploratory and use the most rudimentary form of analysis'. However, McCutcheon and Meredith (1993) claim that misapplications of the term 'case study' has also affected the reputation of the research method, for instance in OM descriptions of implementations of new techniques are often called 'case studies'.

A second commonly cited weakness concerns the population to which the findings can be generalised – external validity. Conventional wisdom claims that case studies, compared with quantitative statistical studies, are weak in their capacity to generalise to other situations. In quantitative studies it is possible to statistically generalise from the data by the detailed analysis of means, correlation's and other methods (Hartley 1994) whereas in case studies no statistical sample is taken therefore this is not possible. However McCutcheon and Meredith (1993) claim that:

> *'no empirical study offers certainty that its findings are valid for other populations. Although field studies and surveys may control for some factors and thereby better define a specific population over which results might be statistically generalised, external validity (the applicability of findings beyond the group) is still an issue for them.'*

In order that rigour in case studies can be improved it must be tested. Yin (2003) proposes four tests to establish the quality of empirical social research:

> ***Construct validity***: establishing correct operational measures for the concepts being studied
>
> ***Internal validity*** (for explanatory or causal studies only, and not for descriptive or exploratory studies): establishing a causal relationship, whereby certain conditions are shown to lead to other conditions, as distinguished from spurious relationships
>
> ***External validity***: establishing the domain to which a studies findings can be generalised
>
> ***Reliability***: demonstrating that the operations of a study – such as the data collection procedures can be repeated, with the same results

In this section the tactics employed to improve the validity of the FPp case studies are explained and discussed:

- triangulation of evidence - a tactic for construct validity
- a number of with-in case and cross-case analytic strategies designed to enhance internal validity
- case selection using replication not sampling logic - a tactic described by Yin (2003) for external validity.

The issue of reliability in data collection is discussed in section 3.5.2 in the operationalisation of the research design.

### *3.4.1 Triangulation (leading to construct validity)*

Triangulation is broadly defined by Denzin (1978) as ‘the combination of methodologies in the study of the same phenomena’. It relies on the principle that collecting different kinds of data bearing on the same phenomena will improve the accuracy of studies if they independently reach similar conclusions, or in other word ‘converge’. Similarly Jick (1979) claims it is largely a vehicle for cross validation stating when two or more distinct methods are found to be congruent and yield comparable data on a phenomenon the results are more valid.

Denzin (1978) argues that 'it is conventionally assumed that triangulation is the use of multiple methods in the study of the same object……but it is only one form of the strategy'. Denzin (1978) and Patton (1987) define four different types of triangulation for doing evaluation, the triangulation:

1) of data sources (data triangulation)
2) among different evaluators (investigator triangulation)
3) of perspectives on the same data set (theory triangulation) and
4) of methods (methodological triangulation)

Two types of triangulation were applied in this research - methodological and data triangulation. Denzin (1978) defined two types of methodological triangulation: 'within-method' and 'between-method'. This research employs the latter 'between-method' approach which Denzin (1978) argues is 'a much more satisfactory form of method triangulation combining dissimilar methods to measure the same unit'. He continues that ' the rationale for this strategy is that the flaws of one method are often the strengths of another; and by combining methods observers can achieve the best of each while overcoming their unique deficiencies.' Three methods were deployed in this research: structured interviews, company documents and field observations. Although it was not possible to use all three methods to collect data on all the concepts a minimum of two methods were always used.

Data triangulation, which involves the use of different sources of data, was the second triangulation type used in this research. Multiple informants were used wherever possible, consequently many of the interviews were repeated with different employees. This was always the case where questions were *opinion*, rather than fact, based. Documentary evidence was often corroborated by evidence from a computer database or management system to improve its validity.

Eisenhardt (1989) suggests that qualitative evidence is 'words' and quantitative evidence 'numbers' and claims that this combination of data types can be highly synergistic. Mintzberg (1979) described this synergy as follows:

> *'For while systematic data create the foundation for our theories, it is the anecdotal data that enable us to do the building. Theory building seems to require rich description, the richness that comes from anecdote. We uncover all kinds of relationships in our hard data, but it is only through the use of this soft data that we are able to explain them.'*

This study involved both quantitative and qualitative evidence (according to Eisenhardt's 1989 definitions). The qualitative evidence was largely 'fact-based', and therefore objective, rather than 'opinion based' and subjective. It corroborated the quantitative evidence, provided a description of how in practical terms FPp was applied and gave explanations for the differences in the outcome variables between the UoAs. For example the qualitative evidence regarding the manufacturing planning and scheduling systems often contributed to an explanation for the differences in order lead-time, demand amplification and excess capacity. Conversely quantitative evidence was often used to support qualitative evidence especially where it was opinion based. For example quantitative evidence was used to support interview evidence regarding problems encountered with the FPp applications. This combination of qualitative and quantitative evidence in the case studies helped to triangulate the research findings

The practical considerations of applying triangulation are addressed in section 3.5.2 on data collection.

### *3.4.2 Analytic Strategy (leading to internal validity)*

Explanatory studies like this one, require internal validity, such that causal relationships (as opposed to spurious relationships) are established whereby certain conditions are shown to lead to other conditions. Accordingly two analytic strategies were applied to this study: pattern matching (Campbell 1975) and Pettigrew's meta-level framework (1990 and 1992).

Yin (2003) identifies a number of tactics for internal (and external validity) and describes pattern matching as 'one of the most desirable strategies'. Pattern matching involves the comparison of an empirically based pattern with a predicted one. If the patterns coincide the results can help a case study strengthen its internal validity. In each of the case studies reported here three units of analysis (UoA) (defined in detail in section 3.1.4) were identified. Each UoA was based around product groups subject to one of three inventory management policies – MTO, FPp and MTS. The measures relating to each of the three UoA were compared and the results compared with those predicted by the hypotheses.

The case study research design maps onto Pettigrew's 'meta-level' analytical framework as explained in section 3.1.3 and shown in Figure 3.2. Pettigrew's framework enables change to be studied in different environments without theory limitations in comparative case study research. There are three primary considerations: context, content and outcome variables as described previously. The outcome variables describe what it is that is being explained. In this study they are the concepts featuring in the hypotheses and described the different outcomes which resulted from applying the three inventory management policies (FPp, MTO and MTS). The change content (the interventions that comprise the change) described what had changed to apply FPp to the original MTO and MTS environment. This provided explanations for why the outcome variables for each UoA were different and why results sometimes deviated from the predicted results.

The Pettigrew framework not only offered a very useful perspective on within case comparisons but also facilitated cross-case comparisons by providing a consistent and meaningful structure for data collection. Cross-case analysis consisted of a search for similarities and differences between the cases (Eisenhardt 1989) in terms of context, change content and outcome variables. Naturally the distinctions between the cases far outweighed the commonalities. This was a feature of the research design which aimed to compare the application of FPp in diverse contexts in order to improve the generalisability of the findings (as discussed in the following section). However in order to advance theories in OM it was necessary to rationalise these differences and seek out commonalities.

As explained for each case the outcome variables were compared with the predicted results defined in the hypotheses through a process known as pattern matching. Some of the hypotheses were *not* supported by all of the cases. Ragin's (1987) view on this is that probabilistic relationships are not accepted in case studies and that all deviating cases must be accounted for. He advises that where cases deviate the evidence collected must be such that the deviation can be explained. In this study a number of deviations, for one particular case were explained by unusual circumstances. However other deviations from predicted results could not be explained so easily and presented a fundamental challenge to hypotheses – disproving the hypotheses even where only one case deviated.

### *3.4.3 Case selection (leading to external validity)*

To what extent are the findings from a case study generalisable beyond the immediate cases – external validity. Yin (2003) explains - that whilst findings from a survey may be generalisable to the population from which the sample was taken - in a case study situation the cases are few, and not statistically sampled, therefore this approach cannot apply. Rather than statistical generalisation, case studies rely on *analytic generalisation,* where the researcher attempts to generalise a particular set of results to some broader theory.

Case selection, much like in the development of experiments, relies on *replication* logic rather than *sampling* logic. Here replication means that individual cases can be used for independent corroboration of specific hypotheses (Eisenhardt 1991). As Ragin (1987) states 'notions of sampling and sampling distributions are less relevant to the case study approach because it is not concerned with the relative distribution of cases with different patterns of causes and effects.' This is precisely why case study research cannot accept probabilistic relationships and instead depends on all deviating cases being accounted for (Ragin 1987). As Harrison (2002) states 'one non-conforming case is sufficient to challenge a theory that should encompass it!'

Ragin (1987) claims in case selection 'more important than relative frequency is the *variety* of meaningful patterns of causes and effects that exist.' In fact Pettigrew (1990) noted that given the limited number of studies which can usually be completed, it makes sense to choose cases such as extreme situations and polar types. Yin (2003) recommends that each case be carefully selected so that it either predicts similar results (literal replication) or produces contrasting results but for predictable reasons (theoretical replication). In this study case selection was on the basis of literal replication since the hypotheses were predicted to be true in all cases.

Finally Eisenhardt (1989) maintains that even in case study research:

> *'the concept of a population is crucial, because the population defines the set of entities from which the research sample is to be drawn. Also selection of an appropriate population controls extraneous variation and helps to define the limits for generalising the findings'.*

The above discussion describes the approach used for case selection in this research and section 3.5.1 describes how this translated into the practical selection of cases.

## 3.5 OPERATIONALISATION OF THE RESEARCH DESIGN

### *3.5.1 Case Selection*

The cases were selected from the domain of manufacturing facilities in England with the aim of providing diverse contexts in which to study the application of FPp. Diversity was sought in terms of the industry and the complexity of the product. As discussed if literal replication was achieved the context diversity would increase the analytic generalisability of the findings. The research design required that during the study period the manufacturing facilities were applying FPp (according to the working definition), MTO (or ETO) and MTS approaches to the manufacture of their products.

A pilot study was required to trial the research design (particularly the use of units of analysis), to firm up the hypotheses and to develop measures or indicators for the concepts featuring in the hypotheses. The Thomas Bolton Flexible Cable factory (TB) in Melling (near Liverpool) was selected. This factory had been part of the BICC Group (my previous employer) and I had worked on a manufacturing improvement project at this factory some 3 years earlier. Naturally this was an ideal site for a pilot study. My existing product and process knowledge, combined with my familiarity with the personnel, enabled me to devote more effort to the design of the study itself.

An initial visit revealed that since my involvement with the factory the FPp approach had been applied to a selection of TB's products. What was not initially clear was that the present day application could no longer be defined as FPp. This was very disappointing and almost prompted me to abandon the study. However after further investigation it was apparent that the data was available to conduct a retrospective study, rather than the planned real-time study. Moreover this study provided the opportunity to examine the demise of a FPp application, which contributed greatly to knowledge on how FPp was applied. In addition it demonstrated the robustness of the research methodology and flexibility of the research design. It set a precedent for the two following cases, in that they were also retrospective studies, even though these manufacturing facilities were applying FPp at the time the study was conducted. The research design did not change in any major way following the pilot study - it followed the research design described in this chapter. Thus the pilot study was treated as a fully validated case study consistent with the two subsequent studies.

Pettigrew (1990) discusses the process of selecting cases:

> *'there is an intentional or design component in the process of choosing and gaining access to research sites, but the practicalities of the process are best characterised by the phrase 'planned opportunism'.*

This is an honest assessment of the approach to case selection for this research. Identifying, and gaining access to, manufacturing facilities in England that were applying FPp, MTO and MTS to significant proportions of their manufacturing proved to be quite a challenge.

At the time of case selection (the year 2001) the application of postponement had been observed as a growing trend in manufacturing and distribution by various surveys (CLM 1995, Ahlstrom and Westbrook 1999). However specific companies - or indeed industry sectors - applying FPp were not identified. Therefore from a study of anecdotal articles, past winners of the UK Best Factory Award (Cranfield School of Management) and various Cranfield academic's industrial contacts a number of companies were identified that were supposed to be applying FPp. Unfortunately further investigation revealed that either:

- the company had ceased to apply FPp,
- the application could not be defined as FPp according to my working definition,
- the company was too small to sustain a study, or
- the timing was wrong for a study.

This exercise provided an indication of which industries were more likely to apply FPp. Using this information the FAME database was searched. This database included all UK registered companies, indeed the database was updated by a non-discriminatory automatic electronic transfer facility from Company House. The FAME organisation added value by ensuring that all the business information and measures provided were standardised across the entrants.

**Table 3.3: Identification of companies applying FPp output from the FAME database searches**

| Industry code (1992 SIC UK codes) | Number of companies | | | |
|---|---|---|---|---|
| | Telephoned | E-mails sent | Replies | FPp applied |
| 3002: Computers and other information processing equipment | 32 | 19 | 3 | 3 |
| 3110: Electric motors, generators and transformers | 35 | 21 | 3 | 1 |
| 3162: Other electric equipment not elsewhere specified | 34 | 22 | 6 | 5 |
| 3210: Electronic valves tubes and other electronic components | 34 | 30 | 12 | 5 |
| 3320: Instruments and appliances for measuring and checking | 39 | 27 | 8 | 7 |

Five different industry codes (1992 SIC UK codes as identified in Table 3.3) were searched using the following search criteria:

- Geographic region – England excluding the Northern and South West regions
- Number of employees – minimum of 100

The companies output from each search were scanned to check that manufacturing was included in their activities. Those companies remaining were telephoned to confirm they had a manufacturing site in England and to identify a suitable contact at the site. Subsequently a standard e-mail was sent to the manufacturing facility providing an introduction to the research, its likely benefits to a participating company and requesting a reply if FPp was being applied.

A surprisingly high number of replies were received and many of them claimed to be applying FPp as Table 3.3 shows. Unfortunately in many of the cases where FPp was 'found':

- it was applied to an insignificant proportion of production,
- MTO nor MTS were applied,
- it was applied intermittently, or
- the company was not interested in participating in the study.

Finally after a number of factory visits Brook Crompton, an electric motor manufacturer and Dewhurst, a manufacturer of control systems were found to satisfy all the criteria and agreed to be studied.

### *3.5.2 Data Collection*

All three studies were conducted retrospectively as explained when defining the UoA (section 3.1.4). Most of the data related to a time period within the 18 month period previous to the commencement of the case study. This raised questions regarding *reliability* of the data. Interview data was required to converge with documentary or database evidence in a triangulating fashion (as described in section 3.4.1). Fortunately, in all three case studies, all the informants were not only still employed at the factory, but in the same roles as for the study period. Therefore all the informants had first hand experience and knowledge of the time period in question. Further the high availability of historic data meant that the retrospective nature of the studies did not harm the completeness of the studies as discussed in further detail within each case study chapter under 'data collection'.

The data to be collected for this research fell into the three categories in Pettigrew's (1990) meta-level framework (as explained in section 3.1.3) context, change content and outcome variables. The data was largely factual although some opinion based data was sought. The 'context' data was largely qualitative and related to the manufacturing facility and the FPp application itself. This data included opinion based data regarding the motivation for applying FPp. The 'change content' data included the operational changes made to apply FPp in the MTO and MTS environment. This included the more opinion based evidence regarding product selection for FPp and problems encountered in applying FPp. Finally the outcome variable data was number based and consisted of a wide range of measures which gauged the outcome of applying FPp.

The initial phase of data collection consisted of interviews (displayed in Appendix 2) with all managers and some other personnel involved with the business processes within the scope of the case studies (indicated in Figure 3.3). Commonly 30 interviews were required with 15 different informants. The interviews were designed to collect the contextual and change content data. In addition they identified other sources of evidence, such as documents, archives and databases which corroborated the interview data and provided further numbers based evidence (indicating the outcome variables).

An interview approach was selected which was appropriate for the nature of the evidence collected. Yin (2003) describes three different types of interviews:

- first is open-ended in which key respondents are asked for facts and opinions about events.
- second is a focussed interview in which the respondent is interviewed for a short period of time normally using a predefined set of questions. These may still be open ended and assume a conversational manner.
- third type of interview is that required for a survey where respondents are required to fill in a questionnaire. This can either be administered by an interviewer or via a postal survey.

The open-ended interview was not appropriate for this research since it largely involved the collection of factual data. On the other hand many of the concepts were sufficiently complex, and open to misinterpretation, that a postal questionnaire was not a reliable data collection method. The most appropriate interview approach appeared to be somewhere between a focussed interview and an administered survey. The interviews were *highly structured* like a survey but also include some open-ended questions such as ‘what were the problems experienced with FPp?’ - the answers to which were normally followed by further questioning.

The interviews involved some concepts that were likely to be unfamiliar to the respondents and others which were complex and open to misinterpretation. To avoid misunderstanding of such concepts (which leads to misinterpretation of the questions) care was taken to ensure that the interviewees had a common and accurate understanding. The glossary in Appendix 1 was at hand throughout the interviews to ensure that the interviewees understood the concepts as intended.

The interviewees were selected on the basis of their knowledge of the processes within the UoA, as illustrated by the fishbone diagram in Figure 3.3. Generally, corroboration between informants was sought when one of the following situations arose:

- the interviewee's knowledge of the subject matter was insufficient, normally not detailed enough
- the data being collected was more subjective or opinion-based

In the former further informants were interviewed until the data was complete. In the latter case all employees that had sufficient knowledge to give a valid response were interviewed. In addition the interviewees were asked to check the interview transcript.

All interviews were taped to ensure that no information was missed and to free the interviewer to concentrate on the interview. Subsequently the interviews were transcribed and compiled whilst not losing the identity of the informants.

## 3.6 LIMITATIONS OF THE RESEARCH DESIGN

No research design is without its limitations. In selecting the multiple case design the study found 'why FPp is applied' and thereby excluded a consideration of why FPp was *not applied at all* in many manufacturing facilities. Other limitations relating to the case orientated approach, such as generalisability, have already been dealt with in section 3.4.

Past research in OM has been largely non-field based and variable oriented. Case based research on the other hand has been criticised for being 'predominantly exploratory and use the most rudimentary form of analysis'. This is *not* a result of limitations in the case based approach rather a result of relatively weak case study research design in the

OM discipline. This study aims to apply the case study approach to provide explanatory findings using a rigorous research design employing sound data gathering techniques and analytical strategies.

The case studies were designed to be broad-based and in-depth taking around five months for data collection and analysis. They involved about thirty interviews with around fifteen different informants to gather the qualitative data and identify sources for the quantitative data. Given the expansive nature of the studies, and the use of three UoAs in each study totalling nine mini case studies, it was decided that three case studies would be sufficient. Only a few case studies were required because case selection, much like in the development of experiments, relies on *replication* logic rather than *sampling* logic (as discussed in section 3.4.3). Here replication means that individual cases can be used for independent corroboration of specific hypotheses (Eisenhardt, 1991). In practice 3 cases proved to be sufficient as by the third and final study theoretical saturation was reached indicated by recurring themes previously found in one of the earlier studies.

# CHAPTER FOUR

## 4 Pilot Study at Thomas Bolton

A pilot study was carried out to reveal any inadequacies in the research design. The Thomas Bolton Flexible Cable factory (TB) in Melling (near Liverpool) was selected. This factory had been part of the BICC Group (my previous employer) and I had worked on a manufacturing improvement project at this factory some 3 years earlier. Naturally this was an ideal site for a pilot study. My existing product and process knowledge, combined with my familiarity with the personnel, enabled me to evaluate the design of the study itself.

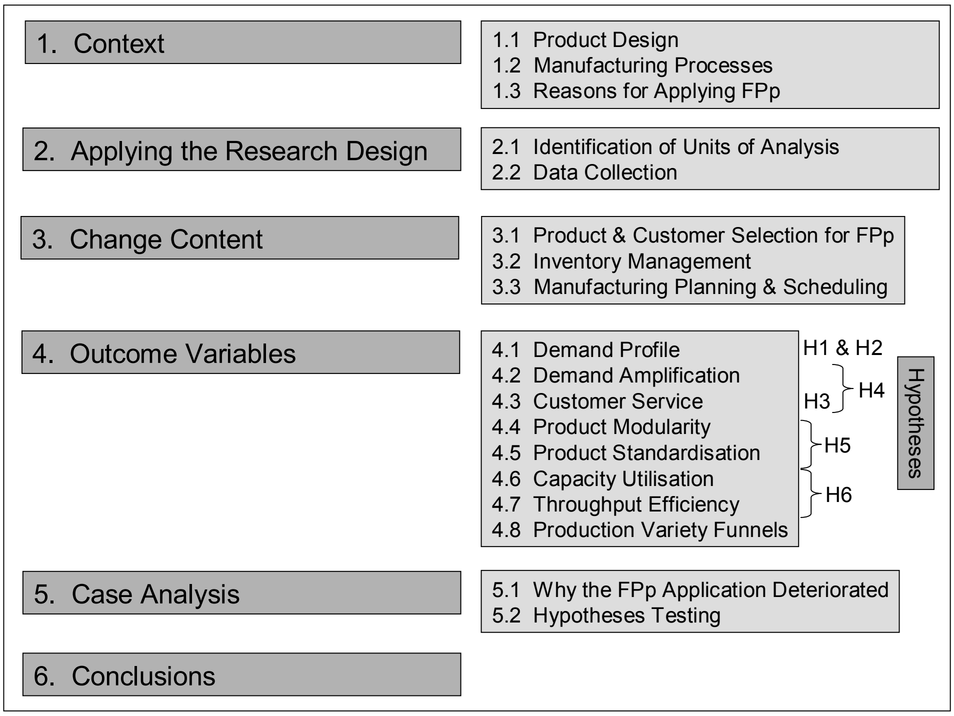



**Figure 4.1: Diagram illustrating the structure of the case study chapters**

An initial visit revealed that since my involvement with the factory the FPp approach had been applied to a selection of TB's products. What was not initially clear was that the present day application could no longer be defined as FPp. This led to a retrospective rather than a real-time study as initially planned. The objectives of the pilot study remained to trial the research design (particularly the use of units of analysis), to firm up the hypotheses and to develop measures or indicators for the concepts featuring in the hypotheses.

In common with the other case study chapters this is structured according to the diagram in Figure 4.1. The contextual features relating to FPp are presented in the first part which includes descriptions of the products subject to FPp, the manufacturing processes used to make them and the reasons for applying FPp. The key aspects of how the research design was applied in this specific study are described in the second part. The ‘change content’ when FPp was applied in a previously MTO and MTS environment is described in the third section. This includes selection of products and customers for FPp, changes to inventory management and manufacturing planning. In the fourth section the ‘outcome variables’, which are the quantitative concepts tested in the hypotheses, are presented. The case analysis is presented in the fifth section which includes an evaluation of the major flaws in the FPp application and testing of the hypotheses against the findings. The chapter closes with conclusions from the study.

## 4.1 CONTEXT

TB designed, manufactured and supplied flexible cables for transmission of information and energy. However, the bulk of cable was low voltage flexible energy cables. TB had a turnover of around £18 million and employed 124 people - 55% of whom were direct manufacturing labour. The financial performance of the factory in 1999 (the year studied) was poor with no profit to report.

The Melling cable factory had been in operation for over 50 years and had been part of the BICC Group - a large multinational corporation supplying cables world-wide. However, in July 1998 the Melling factory was sold to the Thomas Bolton Group, a small group of diverse factories, which was in stark contrast to the large well-established multinational BICC group. The impact on the TB management was dramatic.

The Group Operations Director together with other senior managers believed that the major impact was on cash management. In BICC the main concern was profit (cash flow to a lesser extent) due to the huge resource provided by the BICC Group.

However, in Thomas Bolton Group Ltd cash flow was critical as the Group Operations Director commented, ‘if we run out of cash one month we won’t be able to pay our suppliers who will cut off supply’. The cash flow issue focussed attention on the working capital employed by inventory particularly finished inventory, which was the most valuable. This was the major impetus for the application of FPp.

TB’s largest customer was Volex Powercords (VP), a supplier of power leads situated within an hour’s drive of TB. VP accounted for 22% of sales in 1999 - 35% if sales to VP’s overseas sites in Asia and Mexico were included. Clearly TB was heavily dependent on this business and it was to this supply that they initially applied FPp in November 1998. At this time the dependence was mutual as the recent cable industry restructure had reduced VP’s cable suppliers to TB and one other. Further, TB was VP’s preferred supplier and in 1997 accounted for 85% of VP’s cable supply. VP’s dependence on TB was compounded by the fact that VP’s manufacturing was limited to cable cutting and adding plugs. Consequently cable supply was a very high proportion of incoming materials.

TB’s long-term plans were to expand the FPp application to other customers and products when the VP supply was established. However, as this case study details, a number of problems created a barrier to this expansion and culminated in the demise of the FPp application after 9 months.

### *4.1.1 Product Design*

The cable group studied was described as a ‘3183Y1.00’ cable which was circular shaped with 3 cores (refer to Appendix 3 for a cross sectional diagram). Each core was made up of a copper conductor (cross sectional area 1mm$^2$) which was insulated with PVC to a thickness suitable for ordinary voltage. The three cores were twisted together to make a ‘laid-up’ cable and then extrusion coated with a PVC sheath. Finally the cable was packed, which sometimes involved rewinding the cable onto despatch reels and loading onto pallets.

Variety in the finished cable was generated from variations in the PVC sheathing compound, winding reel and other packaging materials. The application of FPp involved making the standardised laid-up cable to stock and postponing the extrusion of the sheath coating (and subsequent packing processes) until receipt of a customer order. The sheathing compound was available in 100 different colours and around 10 PVC types. The reels onto which the cable was wound for despatch were either ‘direct wound’ reels or despatch reels. The ‘direct wound’ reels were standardised metal reels and (as the name suggests) were designed to be wound with cable directly from the sheath extruder. The despatch reel was available in a range of materials, cardboard, plywood or steel and in many different sizes to accommodate different cable lengths.

### *4.1.2 Manufacturing Processes*

The process of cable making could be described as ‘a semi-continuous process’ in that length - as opposed to discrete parts - is processed. Cable length could be an additional variable at each stage of the manufacturing process. At TB cable length was standardised at each process. However cable length remained a variable at the finished product stage where the customer specified a certain reel length.

The flow process chart in Table 4.1 shows the processes required to make the cables studied. Copper rod was drawn into multi-end wire which was subsequently bunched (twisted together) to form the conductor. The conductor was extruded with a layer of PVC to make the cores – each of a different colour. Then the cores were laid up (twisted together) to give the laid up cable - the generic stock for the FPp approach. Finally the cable was extruded with a final layer of PVC called the sheath. Cable that was ‘direct wound’ (DW) was wound directly onto a despatch reel from the sheath extruder thereby eliminating the rewinding process. This applied to all the cables in the FPp UoA and all but eight cables in the MTO and MTS UoAs.

**Table 4.1: A flow process chart for cables manufactured in the Volume Flex area**

| ***Process Description*** | ***Symbols*** | | | |
|---|---|---|---|---|
| **Wire drawing** | ● | □ | ⇨ | ▽ |
| Store wire by wire drawing machines | ○ | □ | ⇨ | ▼ |
| Move wire to bunching machines | ○ | □ | ➡ | ▽ |
| **Bunch wire** | ● | □ | ⇨ | ▽ |
| Move bunch to wire drawing stores | ○ | □ | ➡ | ▽ |
| Store bunch in wire stores | ○ | □ | ⇨ | ▼ |
| Move bunch to core extruders | ○ | □ | ➡ | ▽ |
| **Core insulation extrusion** | ● | □ | ⇨ | ▽ |
| Move cores to lay-up machines | ○ | □ | ➡ | ▽ |
| Store cores by lay-up machines | ○ | □ | ⇨ | ▼ |
| **Lay-up brown, blue and green/yellow cores** | ● | □ | ⇨ | ▽ |
| Move laid up cable to sheathing machines | ○ | □ | ➡ | ▽ |
| Store laid up cable near sheathing machines | ○ | □ | ⇨ | ▼ |
| **Sheath extrusion** | ● | □ | ⇨ | ▽ |
| Electrical and physical testing of all cables | ○ | ■ | ⇨ | ▽ |
| Move cable to winding machines | ○ | □ | ➡ | ▽ |
| **Rewind onto despatch reels** | ● | □ | ⇨ | ▽ |
| Move reels of cable to finished cable warehouse | ○ | □ | ➡ | ▽ |
| Store reels of cable in warehouse | ○ | □ | ⇨ | ▼ |
| Despatch reels of cable to customer | ○ | □ | ➡ | ▽ |
| **Operation** | ○ | | | |
| **Inspection** | | □ | | |
| **Transport** | | | ⇨ | |
| **Storage** | | | | ▽ |

### *4.1.3 Reasons for Applying Form Postponement*

The reasons for applying FPp (and how it was applied) was the subject of interviews with five different informants. The informants were selected because they were closely associated with the implementation of FPp. The informants were the Supply Chain Manager, the Works Manager, the Commercial Director, the Business Manager and finally the main contact at the customers, VP. Each informant was asked:

***Why was FPp applied - what were the drivers?***

The initiative to apply FPp came from TB who applied it to selected cables for VP. The main reason for its application (quoted by all interviewees including the VP representative) was to increase responsiveness of cable supply. It was envisaged that this would enable finished stocks at TB to be reduced by improving the match between TB cable supply and VP demand. The Supply Chain Manager described the original vision:

> *'the Thomas Bolton factory was to become so responsive that the end of Thomas Bolton production line would be the start of Volex's production line'.*

Matching TB's cable supply to VP's demand was not easy, in part because demand was extremely variable. This was exacerbated by the fact that TB was one of only two cable suppliers to VP. The other supplier was Ericsson in Sweden who due to its remoteness and inherent lack of responsiveness was only awarded 15% of VP's business. Moreover as admitted by the VP representative:

> *'the orders placed with Ericsson were firm monthly orders whilst TB absorbed the variability in demand'*

The VP representative described the problems with the cable supply from TB:

> *'in the past the supply of cables [MTO] from Thomas Bolton had led to either 'feast' [excessive stock] or 'famine' [insufficient stock] of different cables.'*

Within the three-week order lead-time the trend in demand for a given cable could reverse. While the stocks of a cable were being ramped down the demand could increase leading to chronic shortages.

The VP representative described the impact on VP of applying FPp to the manufacture of the cables:

> *'it brought the ordering horizon in from next month to next week so cable stocks at TB could be controlled with more certainty - less reliant on sales forecasts and more reliant on our [VP] customer's orders.'*

The TB Supply Chain Manager claimed the application of FPp was driven by increased competition for the VP business and the need to reduce cable stocks. First consider the competitive issue. VP (including Asia and Mexico) was TB's biggest customer and accounted for 35% by volume of sales so it was imperative that their custom was retained. European overseas cable manufacturers were planning to set up a cable warehouse in the UK so, as the Supply Chain Manager commented:

> *'FPp was Thomas Bolton's answer to that threat, making it very difficult for the competing overseas cable suppliers to offer the same responsiveness'.*

With regards to finished stock cash flow had become critical when the Melling factory was bought by a small company (Thomas Bolton). As a result there was intense pressure to reduce the working capital employed by finished inventory.

***Summary:*** the reason for applying FPp according to both TB and VP was to increase responsiveness so that the TB cable supply more closely matched VP's demand for cable. However the two companies were driven by different motives. VP on the one hand wanted to avoid the 'feast and famine' supply associated with MTO. TB on the other hand wanted to fight off competition for the VP business and at the same time reduce the very high levels of finished stock they held.

## 4.2 APPLYING THE RESEARCH DESIGN

The identification of the units of analysis and the various issues concerned with data collection at TB are addressed in this section.

### *4.2.1 Identification of Units of Analysis*

In TB there were two main manufacturing areas:

- one which had the capability to produce the full range of cables and manufactured the low volume, specialised cables, and
- the 'Volume Flex' area, which had limited capability but manufactured the high volume products, including almost all the cables supplied to VP.

Both these areas were supplied by copper conductors from the 'Conductor Forming' area and cable produced in them was sometimes rewound onto despatch reels in the 'Winding' area.

All the products subjected to FPp were manufactured exclusively in the Volume Flex area. Here cables were made according to a number of inventory management policies. As a result the study was confined to the Volume Flex area. The Conductor Forming area was scoped out of the study since the copper wire was drawn speculatively (to a common stock for all cables) regardless of inventory management policy. However, the Winding area was scoped *into* the study, because rewinding the cables onto smaller reels was a manufacturing process - commonly performed to customer order - but sometimes speculatively.

Each UoA was based around a *product family* subject to a particular *inventory management policy* (FPp, MTO/ETO, and MTS) and the respective customer orders due for delivery within a *certain time frame*. Considering the *time frame* dimension first. FPp was initially applied in November 1998 and customer order records showed that the approach was properly established by the beginning of January 1999. The chronology of changes to the FPp application (Appendix 4) shows that by mid-September 1999 the order lead-time had been extended, such that it could no longer be defined as FPp. Accordingly the time period for the study was limited to between 1$^{st}$ January and 1$^{st}$ September 1999.

During the first week in June 1999 there was a factory shutdown and the new integrated business system went ‘live’. The new system caused major disruption particularly to records such as customer orders. Further, the finished stock records for cables subject to FPp (Appendix 3) show that stock levels were generally higher in the second half, than the first half, of 1999. Consequently the period from 1$^{st}$ January to 31$^{st}$ May 1999 was studied.

Identifying the appropriate *product families* for each UoA was not easy, because no one product family was exclusively manufactured according to one inventory management policy (as Table 4.2 illustrates). Inventory management policies at TB were normally dictated by the customer, rather than set by product. The MTS approach was split between make-to-dedicated stock and make-to-speculative stock. However, during the study period the make-to-speculative-stock approach only accounted for about 4% of the volume manufactured in the Volume Flex area - an insufficient volume for a UoA.

The volume sales (calculated from sales invoices) of the eight top selling cable product groups are shown in Table 4.2. Overall these eight cable groups accounted for 90% of sales. The FPp approach was applied to five different cable groups and the two groups produced (under FPp) in the highest volumes were 3183Y1.00 and 3182Y1.00. The 3183Y1.00 cable group was selected for the UoA, because it accounted for the greatest proportion of cable sales overall - 20% of cables manufactured in the Volume Flex area were 3183Y1.00.

**Table 4.2: Sales volumes for cables produced in the Volume Flex area and despatched between January and July 1999.**

| *Cable* | *MTO* | | *FPp* | | *Make-to-dedicated-stock* | | *TOTAL* | |
|---|---|---|---|---|---|---|---|---|
| | *km* | *% of MTO* | *km* | *% of FPp* | *km* | *% of MTS* | *km* | *% of total* |
| ***3183Y1.00*** | 8785 | 22% | 7000 | 30% | 1318 | 7% | ***17320*** | ***20%*** |
| ***2192Y0.75*** | 10000 | 25% | 0 | 0% | 549 | 3% | ***10571*** | ***12%*** |
| ***3182Y1.00*** | 1625 | 4% | 6734 | 29% | 1419 | 7% | ***9801*** | ***12%*** |
| ***3183Y0.75*** | 5117 | 13% | 1941 | 8% | 2080 | 11% | ***9329*** | ***11%*** |
| ***3182Y0.75*** | 551 | 1% | 4361 | 19% | 3055 | 16% | ***9122*** | ***11%*** |
| ***3183Y1.25*** | 2613 | 7% | 0 | 0% | 5275 | 27% | ***7888*** | ***9%*** |
| ***3182Y0.50*** | 1375 | 4% | 3129 | 14% | 2335 | 12% | ***6840*** | ***8%*** |
| ***3183Y1.50*** | 3624 | 9% | 0 | 0% | 1112 | 6% | ***5401*** | ***6%*** |
| *TOTAL* | ***33691*** | ***85%*** | ***23165*** | ***100%*** | ***17143*** | ***88%*** | ***76272*** | ***90%*** |
| *% of total* | ***44%*** | | ***30%*** | | ***22%*** | | ***100%*** | |

**Note: This table excludes the 4% of sales volume produced in Volume Flex under the ‘made-to-speculative-stock’ inventory management policy**

Ideally the product groups selected for the three UoAs should be as similar as possible in terms of general design and manufacturing processes. This ensures that the comparison between the different inventory management policies (FPp, MTO and MTS), in terms of the various measures, screens out product specific factors. In light of this consideration the 3183Y1.00 cable was also chosen for the MTO UoA and the MTS UoA. However, there was a concern that the MTS UoA would be too small and not encapsulate enough orders because it only accounted for a fifth of the cable sales that the FPp UoA covered. Fortunately this was not the case.

To conclude the finished product items to be included in each UoA were those 31813Y1.00 cables due for delivery between 1st January and 31st May 1999 (as listed in Appendix 5). Comparing FPp with the MTO approach for cables supplied to VP is a ‘before and after’ type comparison because, prior to the application of FPp, all VP orders were MTO.

Before leaving the identification of the UoA it is useful to view them in terms of the customers they involved. The top eleven customers, by sales value, are shown in Appendix 6 and seven of these were included in the UoA.

### *4.2.2 Data Collection*

This was a retrospective study where the majority of the data collected applied to the period between 1st January and 31st May 1999 - about 18 months before the study was conducted (July to October 2000). This raised questions regarding the *reliability* of the data. Interview data required support from documentary evidence, and fortunately all the interviewees were not only still employed at the factory but in the same roles as for the study period. This meant that all the informants had first hand experience and knowledge of the time period in question.

A particularly pertinent archival document was a report written by the Supply Chain Manager at the time of the initial implementation of FPp. It described the application of FPp in detail and substantiated much of the interview evidence regarding inventory management and manufacturing planning and scheduling procedures.

Unfortunately just after the study period, 1st June 1999, the new integrated business system went ‘live’ and the old business system (including the OMAC MRP system) was rendered obsolete and *inaccessible*. This meant that electronic data on customer order processing was unavailable and instead the study relied on the availability of hard copies of customer orders and call offs. Generally this documentary evidence was available. However some customer orders were missing as detailed in section 4.4.

A particularly fruitful source of evidence for the *performance measures* was the Production Monitoring and Control System (PMCS), which allowed the sequencing and allocation of jobs onto individual machines and monitored their progress through the factory. PMCS covered all processes within the study scope and provided the production schedules and shipping records necessary to measure demand amplification, order lead-time and delivery reliability. With regards to reliability the data retrieved from PMCS was no less reliable (or accessible) during the study than when it was generated.

The retrospective nature of the study did have some drawbacks. It was not possible to measure demand amplification, ex-stock availability and throughput efficiency for the MTS UoA. Conversely the retrospective approach offered benefits. During the study period a manufacturing database measuring Overall Equipment Effectiveness (a measure of capacity utilisation) was maintained. This database fell into disuse the year after and therefore would not have been available for a real time study. A further benefit of the retrospective study was the opportunity to examine the deterioration of a FPp application.

Overall the reliability and completeness of the data were only marginally affected by the retrospective nature of the study.

## 4.3 CHANGE CONTENT

In this section the changes required to apply FPp in a MTS and MTO environment are described including: product and customer selection, inventory management and manufacturing planning and scheduling changes.

### *4.3.1 Product and Customer Selection for Form Postponement*

In common with 'the reasons for applying FPp', how products and customers were selected for FPp was the subject of interviews with five different informants (previously listed in section 4.1.3). The two questions asked of all informants, and their collective answers, are presented below:

***Was the FPp approach limited to certain customer, and if so why?***

TB limited the application of FPp to cables supplied to VP because of problems adapting the existing production scheduling system to support FPp (refer to section 4.3.3 for a detailed discussion).

The first problem was the control of the generic cable stock levels. This was critical - a shortage in these stocks would almost certainly have resulted in a late delivery. No Kanban system or forecasting package was used to control the stock levels. The Scheduling Manager simply anticipated laid up cable requirements based on his view of laid up cable consumption or gut feeling. It was ‘not scientific’. This was difficult enough for one customer and it was felt it would be impossible for more than one.

The second problem concerned the limitation of the scheduling system to weekly time buckets rather than daily, as required for FPp. This necessitated the use of a very simple manual planning board for scheduling FPp customer orders through the postponed sheathing process. The expectation was that this planning board would prove inadequate for the task of scheduling multiple customers and a larger, more complex, planning board would be required.

***Was the FPp approach limited to certain product specifications, and if so why?***

The finished cables subject to FPp were largely selected by VP on the basis of the volume they consumed. Those used at the highest rates - categorised as ‘runners’ - were selected.

When TB first approached VP about FPp TB were supplying about 50 different finished cables to VP. The VP representative split these cables into three categories ‘runners’, ‘repeaters’ and ‘strangers’ according to the volume (average weekly useage) and frequency of useage at VP (daily, weekly etc).

- ***runners*** were the high volume cables that were used by VP *daily*
- ***repeaters*** were used *weekly*
- ***strangers*** were only *occasionally* used and were generally cables required for a specific VP customer.

Data used by VP to conduct this analysis was unavailable. However the report describing the application of FPp (written by the Supply Chain Manager) provided some relevant sales data for the year prior to the FPp implementation. This data showed that four out of five of the cable groups selected for FPp were in the top six selling cables of 1997, which accounted for 85% by volume of the 1997 sales.

In general the cables classed as 'runners' were selected for manufacture under the FPp approach. Cables were categorised by VP according to useage at *finished* cable level not at cable group (or the *generic*) level. For a given generic cable, some finished cable variants were therefore subjected to FPp whilst others, with only a different sheath colour, were supplied under the MTO approach.

Given the improved responsiveness why was FPp only applied to 'runners', why not 'repeaters' and 'strangers' that used the same generic cable? The answer lay in the supply of the sheathing compound used in the postponed process. For all cables subject to FPp the sheathing compound was required on consignment stock. This involved the supplier maintaining a stock of compound specifically for TB such that it was available within 24 hours. TB purchased upon consumption, however a consignment stock was not without risk for TB as they were committed to purchase it within a certain time period. As a consequence where cables were not categorised as 'runners' the risk of obsolescence (or the supplier refusing to provide a consignment stock) was high hence TB did not offer FPp. Exceptionally the white cable subject to FPp was not categorised as a 'runner'. However, the white sheathing compound was already available on consignment stock.

### *4.3.2 Inventory management*

Inventory management encompassed order processing and the subsequent control of stocks, including laid-up cables and finished cables. Also considered in this section - and inherent in the inventory management approach - is the Customer Order Decoupling Point (CODP) location.

Evidence for inventory management was gathered from interviews with the Commercial Director, Sales Manager, Supply Chain Manager and the two Customer Service Assistants dealing with the respective customers. The key features of the three inventory management policies studied are presented in Table 4.3.

Cables were manufactured using the FPp approach for one customer only - Volex Powercords (VP). The cable orders from VP were processed according to a weekly cycle as illustrated in Figure 4.2. Every Tuesday VP supplied an order schedule for cables subject to FPp. The order schedule specified the quantity of each finished cable to be available each day.

Prior to the application of FPp, cables were MTO for VP. Unlike other MTO customers - who accepted delivery upon completion - VP was given ‘special treatment’ and allowed to call-off finished cable. VP only called off cable when required, since they were invoiced upon despatch. Therefore, TB effectively held VP cable stocks which VP controlled by placing orders and call-offs.

**Table 4.3: The main features of the inventory management policies compared for the UoA.**

| ***Features*** | ***MTO*** | ***FPp*** | ***MTS*** |
|---|---|---|---|
| ***Demand information from the customer*** | Purchase orders | Blanket orders<br>Weekly Order Schedule | Forward schedules<br>Call-off sheets |
| ***Standard quoted lead-time*** | 21 days | 6 to 10 days<br>(depending on due day) | 1 day |
| ***Components for order-driven processes*** | Drawn wire and PVC polymers | 5 laid up cables and PVC polymers | n/a |
| ***Component supply*** | Drawn wire…stock replenishment | Laid up cable… Scheduling Manager monitored stock levels and released replenishment orders | Finished cable…OPD released stock replenishment orders based on ASR suggestions |
| | PVC polymers….supplier consignment stocks. TB was invoiced upon useage | | |
| ***Finished cable stocks*** | Only for VP | For VP (only customer) | For all customers |
| ***Finished cable deliveries*** | Delivered upon completion (VP called-off) | VP called-off daily | All customers called-off |
| ***CODP location*** | Drawn wire | Laid up cable | Finished cable |

When FPp was implemented TB continued to allow VP to call-off the finished cable. However, VP agreed that they would call-off upon completion, thereby allowing FPp to eliminate finished stocks. Finished stocks persisted, as the chart of finished ‘3183Y1.00’ cable stock in Appendix 3 shows. The stocks recorded for the first 5 weeks of 1999 were largely remaining stocks from the latter months of 1998, when FPp was being implemented. The chart shows that when these stocks were finally consumed stock levels dropped dramatically to 0.1 weeks forward cover. However after just 2 weeks stock levels climbed up again. The average forward cover of 3183Y1.00 finished cable subject to FPp (for the year 1999) was the same as that for the study period at 0.7 weeks cover.

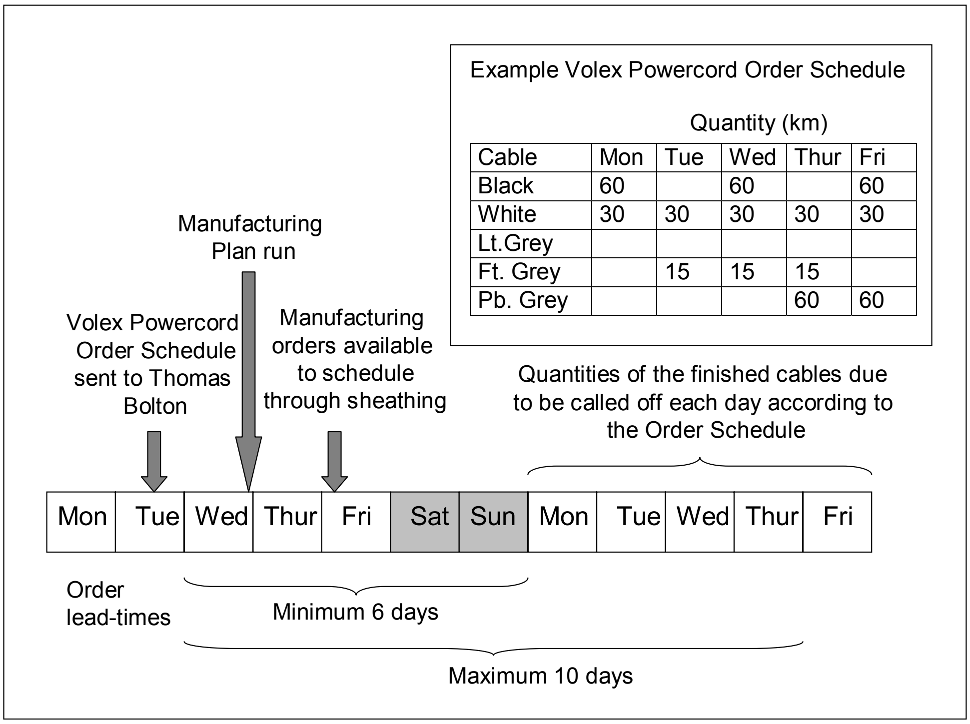



**Figure 4.2: A time line for the FPp inventory management policy**

Standard quoted lead-times for orders subject to FPp was between 6 and 10 days, depending on the scheduled call-off day, as illustrated in Figure 4.2. This compared favourably with the 21 days standard quoted lead-time previously offered for the MTO approach. However, even with this level of improved responsiveness VP were still not able to match TB cable supply with their requirements therefore finished stocks persisted.

The sheathing compound, for all cables subject to FPp, was required on consignment stock. This stock was maintained by the compound supplier and therefore available within 24 hours and only paid for upon useage. However, TB was committed to purchase the consignment stock within a given time period.

There were significant difficulties in adapting the manufacturing system for FPp and the Supply Chain Manager commented that

> *'the biggest problem was controlling the generic cable stock to ensure high ex-stock availability'.*

To aid laid-up cable stock control the Order Processing Department (OPD) sent a copy of the VP Order Schedule on Tuesday (upon receipt) to the Scheduling Manager. This provided him with advanced warning of the following weeks laid-up cable requirements. However no Kanban system, or forecasting package, was used to control the laid-up cable stock levels. Instead cable requirements were estimated based on the Scheduling Manager's view of cable consumption or 'gut feeling' - it was 'not scientific'. As a result the stock levels varied greatly between 0.1 and 1.9 weeks cover (as the chart in Appendix 3 shows).

### *4.3.3 Manufacturing Planning and Scheduling*

Manufacturing planning and scheduling covers the process from the orders being present on the Master Production Schedule (MPS) to factory orders being scheduled and monitored through the operations. Evidence was gathered via interviews with the Scheduling Manager, the Supply Chain Manager and the Works Manager. This was supported by a report written by the Supply Chain Manager during the implementation of FPp, which described changes to the manufacturing planning and scheduling process.

The manufacturing planning process for customer orders and stock replenishment orders is represented in Figure 4.3. This data flow diagram illustrates the process from orders being present on the one week period MPS to manufacturing jobs being available on PMCS (Production Monitoring and Control System) for allocation to individual machines.

The main features of the manufacturing planning and scheduling process for the three UoA are compared in Table 4.4. Orders subject to FPp were always received and logged onto the SOB on Tuesday, whereas orders for MTO cables or MTS cables were logged onto the SOB any day of the week. The Preplan was the first stage of the manufacturing planning process and was performed once a week. For FPp orders the Preplan was run over Wednesday night such that manufacturing jobs were available on PMCS, for allocation to the sheath extruders, on Friday morning. This allowed cable due to be available 6.00am Monday morning to be processed either Friday or on overtime over the weekend.

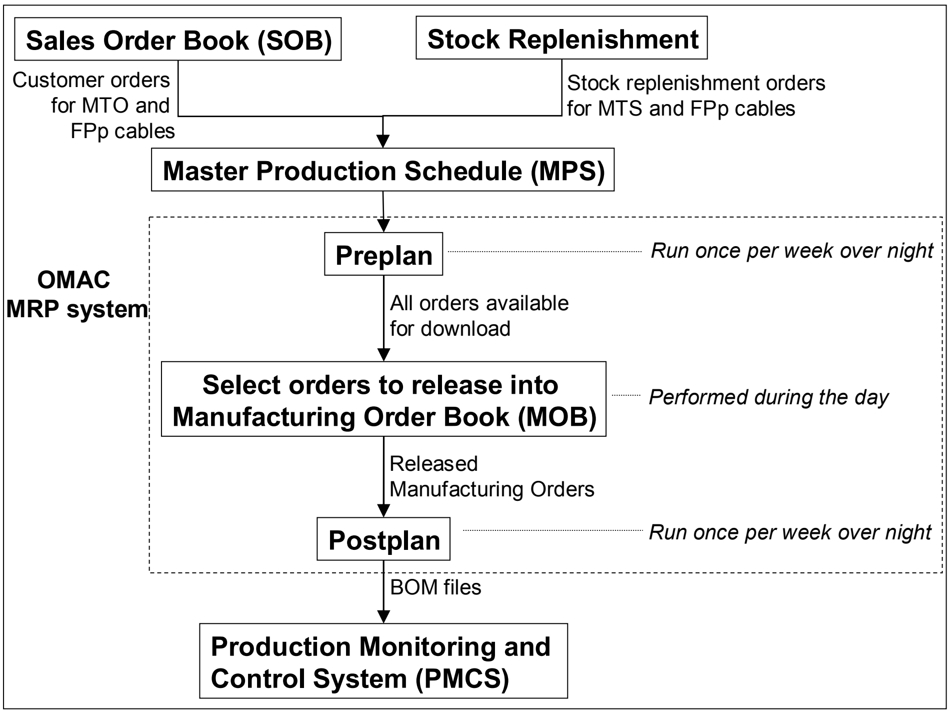



**Figure 4.3: A data flow diagram showing the Manufacturing Planning Process**

With the exception of bringing the Preplan forward to Tuesday night, this procedure reduced the order processing and planning lead-time to a minimum of 3 days (given the existing manufacturing planning systems). At first glance this appeared a significant improvement on the 4 to 8 day processing time for MTO cables, however (as described in section 4.5.1) this was not the case and led to the deterioration of the FPp application.

For MTO cable orders and stock replenishment orders (including FPp laid-up cable stocks) the Preplan was run on Friday night. Therefore the manufacturing jobs were available on PMCS for allocation to the bunch machines on Tuesday morning. At best if a sales order was logged on the SOB on Friday (and therefore included in the Preplan that night) the order processing and planning procedure still accounted for 4 days. In the *worst* case where orders were received on the Monday the procedure accounted for 8 days.

**Table 4.4: Main features of manufacturing planning compared for MTO and FPp.**

| *Features* | *Stock Replenishment Orders* | *MTO* | *FPp* |
|---|---|---|---|
| *Manufacturing Orders* | Processed by MRP system driven by one week period MPS | | |
| *Customer Orders entered onto SOB* | n/a | Anytime during the week | Tuesday morning |
| *Preplan run once each week* | Friday night | | Wednesday night |
| *Manufacturing orders released onto PMCS* | Tuesday morning | | Friday morning |
| *Duration of manufacturing planning process* | 84 hours over 4 nights (due to weekend) | | 36 hours over 2 nights |
| *Order processing and manufacturing planning lead-time* | n/a | 4 to 8 days (depending on day of week order was received) | 3 days (excludes possible waiting time of 6 days) |

Once manufacturing jobs were available on PMCS the Scheduling Manager batched similar jobs together to minimise changeovers. Batching was very pronounced at the bunching process. However it reduced with increases in variety and at the sheathing process was minimal (refer to Appendix 3 for batching procedures).

There were significant difficulties adapting the production scheduling process for FPp. These difficulties limited the application of FPp to one customer as described in section 4.3.1. Controlling the laid-up cable stock (as described in the previous section) was one problem and the limitation of the manufacturing planning system to due weeks, rather than due days, was another. This was a procedural, rather than software, limitation attributable to the weekly time buckets used in the MRP system. The implications for the FPp application were two-fold:

- Firstly, the Scheduling manager did not know the daily due dates (only the due weeks) from PMCS. Therefore OPD was required to send a copy of the VP Order Schedule upon receipt. This procedure had the added benefit of by-passing the lengthy manufacturing planning process, and providing the Scheduling Manager with advance warning of the following weeks requirements.

- Secondly, scheduling orders through the postponed sheathing process was not possible using PMCS alone. A very simple *manual planning board* was also used.

## 4.4 OUTCOME VARIABLES

The measures taken will be presented and compared for the three UoAs over the following eight sub-sections. The first section presents the demand profile measures, demand volume, mix and variability. In the second section the demand amplification plots are discussed. The customer service measures including ex-stock availability, order lead-time and delivery reliability are analysed in the third section. The fourth and fifth sections address product modularity and standardisation. Capacity utilisation measures and throughput efficiency measures are presented in the next two sections and finally the production variety funnels are compared.

### *4.4.1 Demand Profile*

Evidence for the three demand measures was gathered from archived customer order and call off documents. It was important for measuring demand variability (and amplification) that the demand placed on the manufacturing system by both domestic, and export, orders was measured in the same time frame. Therefore the ex-works due date was taken as the delivery due date for all orders with the proviso that for export there was a transit time (refer to Appendix 7 for a detailed explanation).

To check that the archived customer order evidence was complete all factory orders for the UoA were identified on PMCS. It was found that *all* archived customer order documents were available for the FPp UoA however for the MTO UoA 21 out of the total of 79 customer order documents were missing. Fortunately the factory order due dates into despatch were known from PMCS and were generally the Saturday before the ex-works due week. Therefore it was possible to estimate the ex-works due date for the missing orders as detailed in Appendix 7.

About half the archived customer call-off documents, for the MTS UoA, were missing. However, the actual ex-works dates for these call-offs were available on PMCS. Further, comparison with existing call-off records revealed that these dates were sufficiently close to the call-off dates to provide accurate *average* demand measures over the five-month study period.

The demand measures for the three UoA are summarised in Table 4.5, for the full statement of demand per finished cable see the tables in Appendix 7. The CV of demand was calculated from the weekly demands for each generic and end item over the five-month study period.

**Table 4.5: The demand measures compared for the UoA.**

| *Measure* | *MTO* | *FPp* | *MTS* |
|---|---|---|---|
| ***No. of orders*** | 79 | 91 | 44 |
| ***Demand mix at end item level (generic level)*** | 18 variants<br>(2) | 5 variants<br>(1) | 15 variants<br>(1) |
| ***Total volume demand*** | 5146 km | 4810 km | 1002 km |
| ***Av. volume demand at end item level (generic level)*** | 286km<br>(2573km) | 962km<br>(4810km) | 69km<br>(1002km) |
| ***Av. CV of demand at end item level (range)*** | 324%<br>(93-458%) | 169%<br>(132 –219%) | 326%<br>(133-458%) |
| ***Av. CV of demand at end generic level (range)*** | 87%<br>(67-107%) | 70% | 86% |

The demand mix was very low for all three UoAs. This was a feature of the Volume Flex production area which exclusively manufactured the higher volume products. The potential number of end items for all three UoA was much greater than the study suggested - in the hundreds rather than the tens of end items. The variety of finished cables was driven by the sheathing compound (as well as packaging materials), which was available in 100 different colours and around 10 PVC types.

Contrary to the hypotheses, cables subject to FPp were demanded in a lower number of variants than the MTS cables - 5 compared to 15 variants respectively. Similarly demand variability at end item level was lower for the FPp UoA than the MTS UoA and volume demand at end item level was lower for the MTS cables than the FPp cables. These unexpected results were due to the combined effects of two factors:

- Firstly, the FPp application was artificially restricted to one customer (albeit the largest) which limited the potential for variations in the product.

- Secondly, in general cables were only selected for manufacture under FPp when they exhibited a volume demand at *end item level* high enough to justify a consignment stock of sheathing polymer.

The demand variability for all three UoA was dramatically reduced when taken at the generic cable - 70% compared to 169% at the finished keypad level for the FPp cables. So clearly keeping stocks at the generic cable level should have permitted the provision of a much lower safety stock than stocking at the finished cable level.

As expected the cables selected for manufacture under FPp rather than MTO exhibited an average volume demand at generic level almost twice that demonstrated by the MTO products. This was a result of variations in the core insulation specification for the MTO cables which resulted in two cables at the generic level rather than one.

***Summary:*** contrary to predictions, both demand mix and demand variability were lower - and demand volume was higher - for cables made under FPp than those made under MTS. These results were attributable to the artificial restriction of FPp to one customer and its application to cables which exhibited a volume demand (end item level) high enough to justify a consignment stock of the sheathing polymer. As expected, products selected for manufacture under FPp rather than MTO exhibited an average demand volume, at generic level, almost twice that demonstrated by the MTO products.

### *4.4.2 Demand Amplification*

It was not possible to measure demand amplification for the MTS UoA because the manufacturing orders could not be traced back through the various manufacturing processes. In addition it would not have been possible for the manufacturing orders (for the MTO or FPp UoA) to exhibit demand amplification because the due dates and quantities were taken directly from the customer orders.

Demand data presented in the previous section was used to measure the demand imposed on the manufacturing system for the FPp and the MTO UoA. The manufacturing schedules were not retrospectively available. However jobs were sequenced and allocated to machines on a daily basis and ‘booked off’ upon completion (by the Operator) on PMCS. Therefore the operation booking off dates were within a day or two of the scheduled output dates and accurately represented the scheduled *sequence of jobs* at each process. This revealed the level to which similar jobs were 'batched' together - important to show demand amplification.

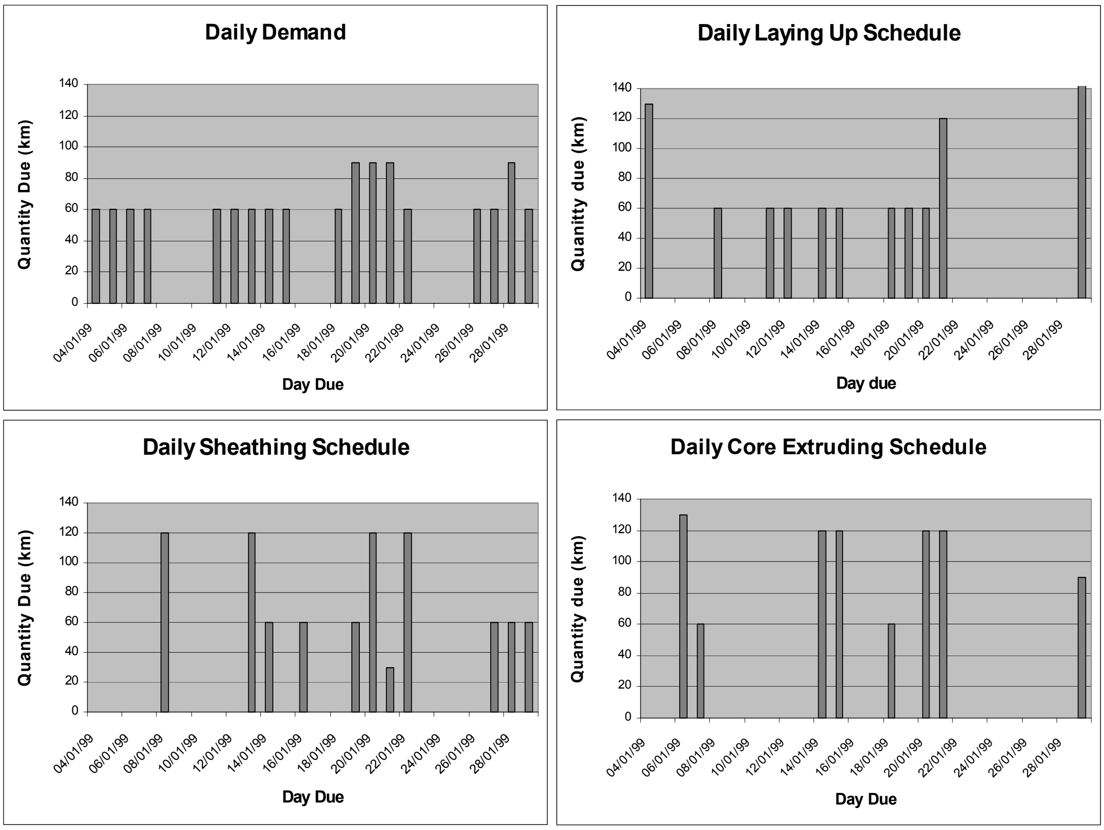



**Figure 4.4: Demand amplification measured at a daily level for the FPp UoA**

The demand amplification charts for the FPp and MTO UoA are shown in Appendix 8. The plots in each chart span the *same weekly time buckets* and use the *same scale* so the relative amplitude of demand can be easily compared. Each chart shows the weekly demand for the cables and the process schedules for sheathing, laying up and core extrusion (in equivalent finished cable length).

Demand amplification was not evident in the charts for either the FPp or MTO UoA when measured at a weekly level. The peaks in demand were of a similar amplitude to the peaks in each of the process schedules. In fact the pattern of demand was quite accurately reflected in the process schedules particularly at laying up and core extrusion.

Products subject to FPp were demanded on a daily basis rather than a weekly basis (as for MTO products). Therefore the daily demand amplification for FPp UoA was plotted over a 4 week period from 4th to 29th January 1999 as shown in Figure 4.4. Demand amplification was evident for the FPp UoA at the daily level particularly at the core extrusion schedule where the peaks and troughs in the schedule were the most pronounced. Even at the order driven sheathing process, where it was not expected, demand amplification was evident. The planning cycle is the most probable cause of this. All orders due during one week were scheduled onto sheathing the week before providing the opportunity to batch up similar jobs.

***Summary:*** no evidence was found of demand amplification when measured at a weekly level for either the FPp or MTO UoA. However, unlike the MTO cables, the FPp cables were demanded on a daily rather than weekly basis. When the demand pattern was plotted at the daily level demand amplification was found for the FPp UoA - even at the order-driven sheathing process where it was not predicted. This was most probably an effect of the long weekly planning cycle, which created the opportunity to batch similar orders together at the sheathing process.

### *4.4.3 Customer Service*

Three measures were used to monitor customer service - order lead-time, delivery performance and ex-stock availability. Unfortunately the data was not available to measure *ex-stock availability* in terms of the proportion of initial *enquiries* for which the correct stock item was available. Further stock records were unavailable for the MTS UoA to indicate ex-stock availability.

The data was unavailable to measure order lead-time and delivery reliability for the MTS UoA. However, this was of little consequence as neither of these measures were tested in the hypotheses for the MTS UoA.

Order lead-time and delivery reliability were not measured by the factory during the study period. To determine these measures both the promised and actual delivery dates were required (for the FPp and MTO UoA). The actual delivery dates were unavailable, therefore the ex-works dates - generally the same as the delivery dates - were used instead (refer to Appendix 9 for a full explanation).

The *promised* and *actual* order lead-times were measured from the receipt of the customer order to the *promised* and *actual* ex-works dates respectively. The evidence for all the dates was gathered from the archived customer order documents with the exception of the actual ex-works dates which were from PMCS. For details on how the order lead-time and delivery reliability measures were calculated refer to Appendix 9.

**Table 4.6: The order lead-time measures for the FPp and MTO UoA.**

| *Measures* | *FPp* | *MTO* | |
|---|---|---|---|
| | | *All other orders* | *Volex Powercord's orders* |
| *No. of orders assessed* | 82 | 30 | 24 |
| *Standard quoted lead-time* | 6 to 10 days | 21 days | |
| *Average promised order lead-time* | 8 days | 49 days | 20 days |
| *Average actual order lead-time* | 16 days | 53 days | 33 days |
| *Average actual order lead-time excl. time in FGS* | 8 days | 42 days | 18 days |
| *Control of deliveries* | VP called-off daily | Delivered upon completion | VP called-off |

The order lead-time measures are presented in Table 4.6. Average promised order lead-time was the same as the standard quoted lead-time for orders subject to FPp - 8 days. However average *actual* order lead-time was double this at 16 days. This was due to VP *not* calling off cables upon completion. If time in FGS, resulting from the delayed call offs, was excluded the actual order lead-time dropped back to 8 days.

It is evident from Table 4.6 that the MTO service offered to VP was far more responsive than that offered to other customers. Both the promised and achieved order lead-times (excluding time in FGS) for the VP orders was less than half that for other customers. The FPp approach improved the responsiveness of the service further. The actual order lead-time (excluding time in FGS) achieved by FPp was one third of the average lead-time achieved by MTO overall (24 days) and just under half of the lead-time achieved by MTO specifically for VP (18 days).

Delivery reliability measures shown in Table 4.7 were calculated by comparing ex-works dates and quantities with customer order due dates and quantities. The delivery reliability achieved by the MTO approach for customers, other than VP, was far better than either the FPp or MTO approach achieved for VP. This was symptomatic of the fact that VP orders were *not* delivered upon completion (as for other customers) but called off at VP's request.

**Table 4.7: The delivery reliability and stock availability measures for the FPp and MTO UoA.**

| Measures | FPp | MTO | |
|---|---|---|---|
| | | All other orders | VP's orders |
| No. of orders assessed | 90 | 30 | 29 |
| Delivery Reliability | | | |
| OTIF (full order delivered by due date) | 13 (14%) | 14 (47%) | 3 (11%) |
| OT (part of order delivered by due date) | 16 (18%) | 4 (13%) | 11 (39%) |
| Order totally undelivered by due date | 61 (68%) | 12 (40%) | 14 (50%) |
| Finished Stock Availability | | | |
| OTIF (full order available on due date) | 46 (51%) | N/a | 22 (76%) |
| OT (part of order available on due date) | 18 (20%) | N/a | 0 |
| Order totally unavailable on due date | 26 (29%) | N/a | 7 (24%) |

A more meaningful measure of TB's ability to deliver VP orders reliably was *stock availability*. Here the date and quantity booked into finished goods was compared with the customer order due date and quantity. Contrary to predictions stock availability was lower for VP orders produced under FPp than those manufactured under the MTO approach - only 51% of FPp orders compared to 76% of MTO orders were available OTIF. The shortfall in stock availability under FPp was largely accounted for by 20% of orders that were only partially available on the due date. Neither the Scheduling nor Supply Chain Manager had clear recollections of why this was the case. A number of possible explanations were provided although no *direct* evidence for them was found. These explanations included: insufficient generic cable stocks; a lack of postponed sheathing capacity (as measured in section 4.4.6), and polymer supply problems into the postponed sheathing process. The latter explanation was discounted because all sheathing polymers used on cables subject to FPp were held on consignment stock.

***Summary:*** actual order lead-time (excluding time in FGS) achieved by FPp was just under half of the order lead-time achieved by MTO for VP. However, delivery reliability was lower for VP orders produced under FPp than those manufactured under the MTO approach - only 51% of FPp orders compared to 76% of MTO orders were available OTIF. The reduced delivery reliability under FPp was largely accounted for by 20% of orders that were only partially available on the due date.

### *4.4.4 Product Modularity*

The relative degree of modularity exhibited by the cables in the three UoA was assessed through interviews with the Technical Manager corroborated by indented BOMs (extracted from the MRP system). A generalised version of the cable indented BOM is illustrated in Figure 4.5.

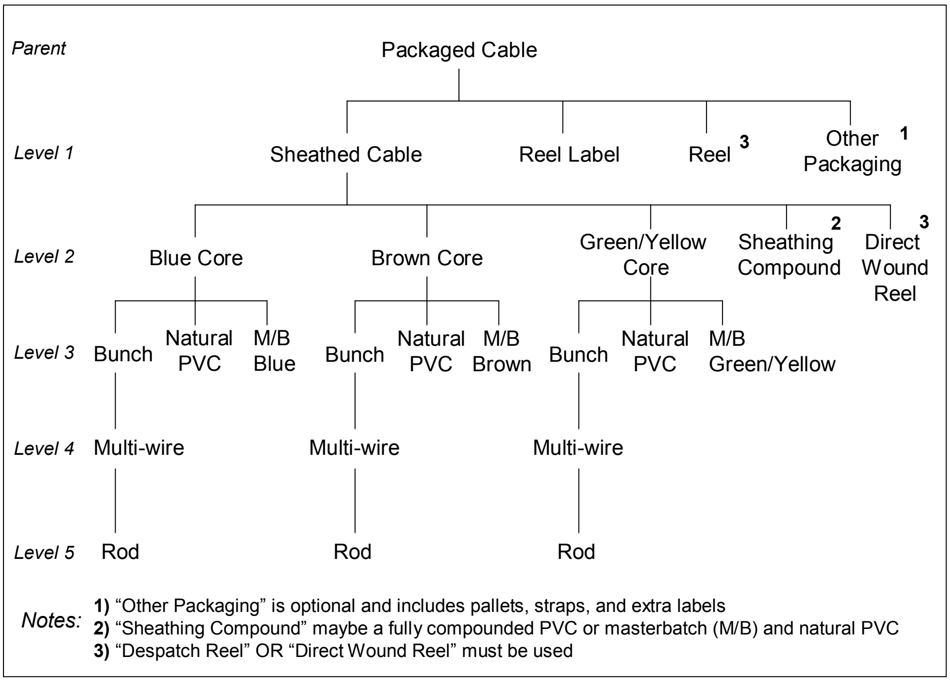



**Figure 4.5: The general indented BOM for the 3183Y1.00 cable**

The cables manufactured by TB were very simple but highly modular. The cores were considered modules each with a discrete function - to transmit an electric current. The sheath also was a module with one function - to mechanically protect the cores. The core could be split into two modules: the copper conductor (or bunch) that transmitted a specific level of electric current; and the PVC coating which insulated the conductor to a specified rating. Finally each of the various items of packaging, such as the reels, fulfilled a single function

With regard to the second characteristic of modularity there was one interference between the modules that was not critical to the function of the product. Adhesion between the core insulation and the sheath coating was ‘positively undesirable’ since the sheath coating must strip away easily from the cores. This unwanted interference was rectified by the application of chalk to discourage the adhesion. Consequently it was only occasionally a problem.

The type of modularity exhibited by the cables was ‘component swapping’ modularity (Pine, 1993). Different components, in this case sheathing polymers, were paired with the same basic product, a laid-up cable, to produce variety in the finished product.

***Summary:*** not only was the entire range of cables equally modular but also highly modular. The generic cable was modular to the same high level as the customising components such as the sheath coating and packaging.

### *4.4.5 Product Standardisation*

The level of product standardisation was indicated by two measures: the proportion of components common to all variants in the UoA and the degree of commonality index.

The full indented BOMs sourced from the MRP BOM module were analysed for the 3183Y1.00 cables within each of the UoA. These BOMs had five levels. Levels 4 and 5 were excluded from the analysis because they were only concerned with the manufacture of one conductor specification (common to all cores in all the cables under study).

A summary of the product standardisation measures is shown in Table 4.8. The number of components in each cable was very similar – 17 or 18. The proportion of common components was highest for the FPp UoA. In fact only two components varied – the polymer and pigment to make the sheath. The MTO UoA had the lowest proportion of common components because three cable specifications used non-standard cores (extruded with a special PVC compound).

The degree of commonality index was measured for three sets of components: the packaging components on BOM level 1; the sheath extrusion components on BOM level 2; and the core extrusion components on BOM level 3. In addition it was calculated over these three BOM levels collectively. The commonality index measures are summarised in Table 4.8 and a detailed explanation of how they were calculated is presented in Appendix 10.

**Table 4.8: Product standardisation measures compared for the UoA**

| ***Measures*** | ***MTO*** | ***FPp*** | ***MTS*** |
|---|---|---|---|
| ***No. of end items*** | 18 variants | 5 variants | 15 variants |
| ***Average no. of components*** | 18 | 17 | 18 |
| ***No. of common components*** | 8 (44%) | 15 (88%) | 13 (72%) |
| ***Degree of commonality index*** | | | |
| ***BOM level 1 packaging components*** | 2 (12%) | 2 (33%) | 2 (14%) |
| ***BOM level 2 sheath extrusion components*** | 4 (19%) | 3 (54%) | 6 (39%) |
| ***BOM level 3 core extrusion components*** | 15 (86%) | 5 (100%) | 15 (100%) |
| ***Over levels 1, 2 and 3*** | 4 (24%) | 3 (61%) | 5 (35%) |

The cables in the FPp UoA exhibited the greatest degree of component commonality at all three levels in the BOM. Supplying only one customer made it possible to standardise the packaging components such as the reels and labels increasing commonality at levels 1 and 2. Further both FPp and MTS were limited to one laid-up cable specification therefore the commonality index at the core extrusion component level was 100%.

***Summary:*** the cables in the FPp UoA exhibited the highest degree of standardisation both in terms of the proportion of common components and the degree of commonality index. This high level of standardisation was made possible by two factors. Firstly, only one customer was supplied with cables subject to FPp which made it possible to standardise the packaging components such as the reels and labels. Secondly, FPp was limited to one laid-up cable specification, or generic cable.

### *4.4.6 Excess Capacity*

Excess capacity was indicated by ‘planned out’ time, Overall Equipment Effectiveness (OEE) and capacity provision. Planned downtime at each work centre was recorded over the study period (though it was excluded from the OEE measure) and it included ‘planned out’ time - the time periods when demand was not expected to require the work centre capacity. In the words of the Works Manager: ‘planned out time was spare capacity’, or excess capacity.

**Table 4.9: Capacity measures for each process between 4th January and 28th March 1999.**

| *Measure* | *Average Weekly Value* | *Standard Deviation* | *Coefficient of Variation (%)* |
|---|---|---|---|
| ***Bunching*** | | | |
| *‘Planned out’ capacity(km)* | 1322 | 458 | 35 |
| *Availability (%)* | 84 | 6 | 7 |
| *Net OEE (%)* | 78 | 5 | 7 |
| ***Core Extrusion*** | | | |
| *‘Planned out’ capacity(km)* | 863 | 435 | 50 |
| *Availability (%)* | 76 | 4 | 6 |
| *Net OEE (%)* | 68 | 4 | 6 |
| ***Laying Up*** | | | |
| *‘Planned out’ capacity(km)* | 1741 | 513 | 29 |
| *Availability (%)* | 79 | 3 | 4 |
| *Net OEE (%)* | 72 | 3 | 5 |
| ***Sheathing Extrusion*** | | | |
| *‘Planned out’ capacity(km)* | 522 | 402 | 77 |
| *Availability (%)* | 78 | 4 | 5 |
| *Net OEE (%)* | 70 | 4 | 6 |

OEE (as defined in the glossary in Appendix 1) was used to measure capacity utilisation at TB for two reasons. Firstly capacity at TB was equipment, rather than labour, driven. Secondly OEE was measured routinely and comprehensively during the study period therefore it was possible to gather the OEE evidence from an established database. The data for the OEE measure was sourced from Short Interval Control sheets completed by the operators detailing all downtime, production rates and defective production.

The OEE data was gathered for the first 12 weeks of 1999 (4th January to 28th March 1999). The 'quality rate' was always 100% because quality defects were not detectable at this stage in production. The 'net performance' tended to be high, in the late 90's in percentage terms, while 'availability' accounted for the bulk of the losses generally measuring between 70% and 80%.

The weekly 'planned out' or excess capacity, the availability and the net OEE for each process were measured over the first 12 weeks of 1999 and are presented in Table 4.9. The availability and net OEE were very similar for core extrusion, laying up and sheath extrusion. These measures were a little higher for bunching because these machines were generally dedicated to a single bunch specification - reducing product changeovers. The variability (indicated by CV) of both availability and net OEE were very low demonstrating that these efficiency measures did not change greatly from week to week. This was not the case for the 'planned out' capacity which was highly variable - probably in response to the high levels of demand variability measured for the 3183Y1.00 cables (refer to section 4.4.1).

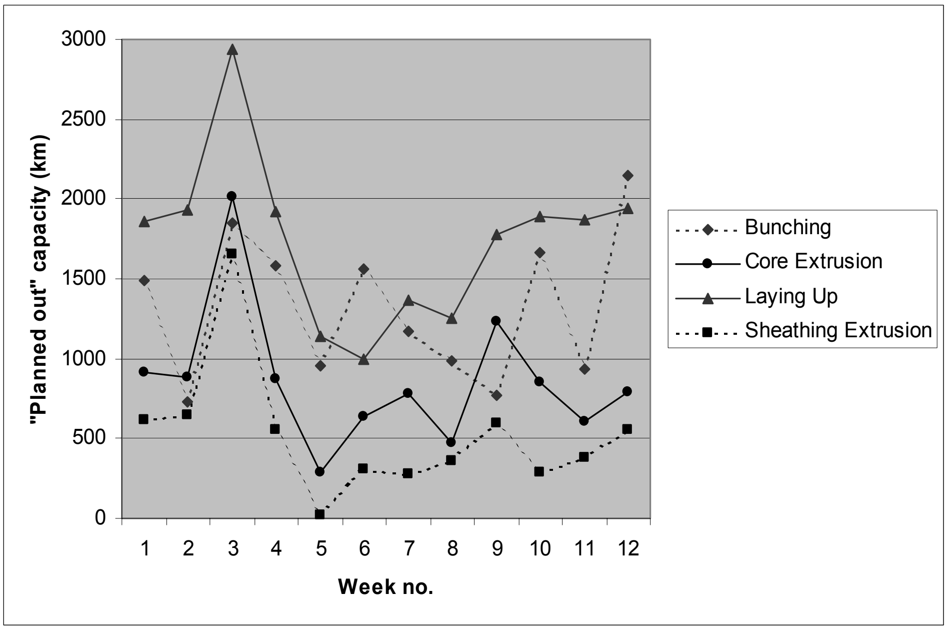



**Figure 4.6: The weekly 'planned out' capacity measured in km of finished 3183Y1.00 cable for each process between 4th January and 28th March 1999**

The weekly measures of planned out capacity are plotted in Figure 4.6. 'Planned out' time at each process was converted into kilometres of finished cabl*e* by assuming this time was used to produce 3183Y1.00 cable only, with no efficiency losses. Over the 12 week period the sheath extrusion process consistently exhibited the least excess capacity - on average less than one third of that present at the laying-up process. While normally laying-up (but sometimes bunching) exhibited the most excess capacity

A crude assessment of available capacity at each process is shown in Table 4.10. Assuming only 3183Y1.00 cable was produced (at the planned production rates) and there were no efficiency losses the production line appeared reasonably well balanced. However, even here sheathing exhibited the least capacity while laying up and bunching exhibited the most, despite the fact sheathing suffers higher efficiency losses due to a higher frequency of changeovers.

**Table 4.10: The capacity in terms of processing rate of finished cable at each process..**

| ***Process*** | ***No. of Machines*** | ***Capacity (km/hr)*** |
|---|---|---|
| ***Bunching*** | 13 | 39 |
| ***Core Extrusion*** | 3 | 36 |
| ***Laying up*** | 4 | 40 |
| ***Sheath Extrusion*** | 3 | 34.5 |

**Note: The capacity is calculated assuming only 3183Y1.00 cable is produced at the planned production rates and there were no efficiency losses.**

***Summary:*** 'planned out' time - the time periods when demand was not expected to require the work centre capacity – was used to indicate excess capacity. The postponed sheathing process consistently exhibited the least 'planned out' time, on average less than one third of that present at the laying up process, which typically exhibited the most. This was *not* due to excessive efficiency losses at the postponed sheathing process as demonstrated by the net OEE which was very similar and consistent for all processes. Rather it resulted from the provision of less capacity at the postponed process contrary to the hypotheses.

### *4.4.7 Throughput Efficiency*

For the cables the value adding activities, within the scope of the study, were the operations identified on the flow process chart in. These operations were bunching, core extrusion, laying-up, sheath extrusion and rewinding.

It was not possible to measure elapsed time taken for jobs at TB because the manufacturing order release dates were not available. Therefore throughput efficiency was measured by tracing jobs back through the value adding processes using the Short Interval Control (SIC) sheets. The SIC sheets were completed by the operators and recorded job start times, finish times and any disruptions such as breakdowns. It was not possible to trace jobs back through the bunching process therefore elapsed time was measured from the start of core extrusion to the output at sheath extrusion. The time period in finished goods stock was not included in the elapsed time measure because, for VP orders, it was controlled by VP not TB. The value added time was the time period recorded on the SIC sheets when the job was being processed at the value adding operations.

**Table 4.11: Throughput efficiency measured from input at core extrusion to output at sheath extrusion for selected FPp and MTO orders.**

| *Date output from Sheathing* | *Order Quantity (km)* | *Value Added time (hrs)* | *Time in stock (hrs)* | | *Excluding time in finished goods* | |
|---|---|---|---|---|---|---|
| | | | *Core* | *Laid Up Cable* | *Elapsed Time (hrs)* | *Throughput Efficiency (%)* |
| ***FPp*** | | | | | | |
| 29 January | 60 | 15.75 | 13 | 11 | 39 | ***40%*** |
| 16 February | 60 | 14.25 | 26 | 65 | 105 | ***14%*** |
| 19 February | 30 | 7.50 | 242 | 209 | 458 | ***2%*** |
| 1 March | 60 | 15.25 | 26 | 106 | 147 | ***10%*** |
| ***MTO*** | | | | | | |
| 20 January | 60 | 19.75 | 37 | 2 | 59 | ***33%*** |
| 12 March | 30 | 7.75 | 30 | 10 | 48 | ***16%*** |

**Note: Two orders were for 30km rather than 60km. To normalise the respective measures the value added times and therefore the throughput efficiency measures can be doubled.**

Due to the laborious nature of tracing jobs through the factory the total number of jobs measured was limited to twelve. For the purposes of comparison between the FPp and MTO UoA the orders sampled from the MTO UoA were restricted to VP orders. In general jobs were sampled taking into account a number of factors (as detailed in Appendix 11) to minimise the effect of variables, other than the inventory management policies themselves.

Four jobs were sampled from each UoA, however it was not possible to trace any of the MTS and two of the MTO jobs through the laying-up process. The throughput efficiency charts are presented in Appendix 11 and a summary of the calculations is shown in Table 4.11.

It is difficult to draw conclusions over such a limited sample. However it does appear that, as expected, the time in core stock is relatively unaffected whilst the time in laid up cable stock is considerably extended for FPp orders. With the exception of the FPp order which achieved a throughput efficiency of 40%, the extended time in laid up cable stock has approximately halved the throughput efficiency of FPp orders compared to MTO orders.

It was not possible to measure the throughput efficiency for the stock driven and order driven processes separately for the FPp orders. Sheathing was the only order driven process and the time an order was booked into finished goods stock was unavailable. This would have meant that the measured elapsed time would have been the same as the value added time on the sheathing process.

### *4.4.8 The Production Variety Funnel*

A PVF which is central to the conceptual model of FPp was plotted for each of the UoA (as shown in Figure 4.7). The BOM data previously used for the product design measures and sourced from the MRP system was used.

The production variety funnel is the same classic 'mushroom' shape, commonly associated with FPp, for all three of the UoA. Indeed if this diagram was drawn for the entire product range manufactured in the Volume Flex area the shape would be the same. Only eight generic cables accounted for 90% (by volume) of production in this area. From a product and process design perspective this suggested that FPp would have been a suitable approach for a much greater proportion of production. Although this may be limited by the need to have the sheathing polymer available ex-stock, which restricts FPp to a predefined set of finished cable items.

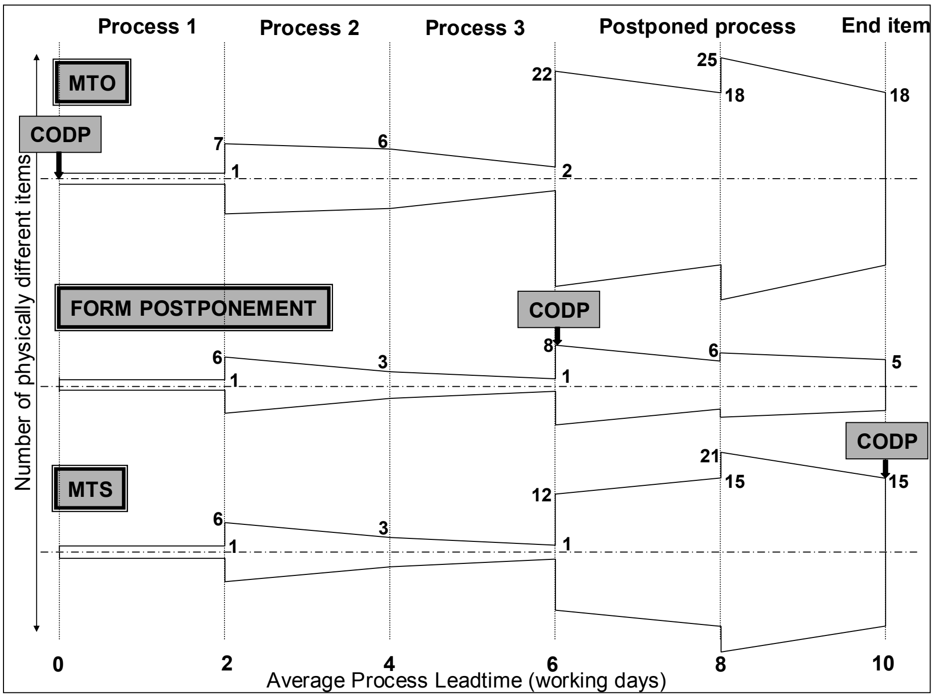



**Figure 4.7: The production variety funnels for the three UoA**

Considering the FPp application there is only one generic cable at the CODP which is transformed into five finished cables. However, a further seven components (sheathing polymer variants and a reel) supplied into the postponed sheathing process must be stocked, therefore there are eight SKUs at the CODP to service only five finished items. Moreover this is an accurate reflection of the number of finished items that are produced given that this product is restricted to one customer.

## 4.5 CASE ANALYSIS

In this section the results of the case analysis are presented: first the major flaws in the FPp application are discussed, and second the findings are compared with the hypotheses.

### *4.5.1 Why the FPp Application Deteriorated*

In this section the major problems experienced with the FPp application, and the changes made to it, are presented. From this and the evidence thus far presented an explanation of why the application deteriorated has been developed.

A chronology of the changes to the FPp application (presented in Appendix 4) was compiled from interview evidence and a complete set of VP Order Schedules (sent to TB between November 1998 and the end of 1999). The interviews were with the Supply Chain Manager, the Sales Manager, the Works Manager and the VP representative.

Originally VP agreed to call-off orders subject to FPp, in full, upon completion - leaving no finished stock at TB. However as the chart of finished cable stock in Appendix 3 shows this was not the case - why? Clearly VP's requirements changed within the order lead-time and the VP representative explained why. The VP Manufacturing Plan was released every Tuesday for the next week and cable orders placed with TB to meet the plan. The Manufacturing Plan was fixed and available four working days before commencing. Unfortunately VP deviated from the plan. According to the VP representative:

> *'it was not uncommon for around 50% of the manufacturing plan to change before implementation'.*

The VP representative gave two reasons why VP deviated from plan. Firstly Production would invariably start producing jobs early. Secondly, VP's customers were regularly offered 7 day order lead-times rather than the standard quoted lead-time of 14 days due to the absence of strategic finished stocks. In either of these cases it was impossible for TB to supply cable on a short enough lead-time to meet VP's new requirements. For example, taking the second case where a 7 day order lead-time was required for a VP customer. TB's order lead-time was between 6 and 10 days. At best VP could place the order on Tuesday and receive it on Monday. But that only left VP with 24 hours to produce, and deliver, the leads. Moreover the probability of it being Tuesday when the order was placed with VP was only 20%!

The order lead-time offered by TB on the FPp cables was largely the result of two major shortfalls in the planning system. Firstly the duration of the planning run was 36 hours over 2 nights, which added a minimum of 2 days to the manufacturing lead time. Secondly the frequency of the planning run was only once per week, which added a potential 6 days of waiting time before new orders could be processed. In the worst case this resulted in a 9 day lead-time before manufacturing could be started - 6 days waiting plus 3 days planning. In effect the planning lead-time for FPp orders had *not* been reduced at all compared to that for MTO orders. An attempt had been made to *synchronise* the TB planning system with the VP planning system. This did not take into account the high level of changes typically made to the VP manufacturing plan between generation and implementation.

The FPp approach allowed the order lead-time to be more than halved compared to MTO. However this was not sufficiently responsive to enable elimination of the finished cable stock. Indeed after 9 months (September 1999) the order lead-time was extended by one week. The existence of high levels of finished goods stock meant it no longer made sense to maintain a generic cable stock in order to manufacture on a short order lead-time. The extended order lead-time meant that even the manufacture of the generic cable was effectively customer-order-driven. This changed the FPp application to a slightly more responsive MTO application

***Conclusion:*** TB's manufacturing planning system was too inflexible to support the FPp application without the support of finished cable buffer stocks. There were two major shortfalls in the planning system: a planning time of 2 days; and a manufacturing planning frequency of once per week - adding a potential 6 days of waiting time before new orders could be processed. In effect the planning lead-time for FPp orders had *not* been reduced at all compared to that for MTO orders. TB's and VP's planning systems were synchronised but this did not take into account VP's high level of deviation from their manufacturing plan.

### *4.5.2 Hypotheses Testing*

The findings from the TB case study were not as predicted by the six hypotheses - one hypothesis was challenged (H1) and three further hypotheses were challenged in part (H4, H5 and H6). One hypothesis remained untested (H3) and another hypothesis was untested in part (H6).

***What is the demand profile of products selected for manufacture under FPp?***

> **H1: Products are selected for manufacture under FPp rather than MTS when they exhibit high demand mix, high demand variability, and low volume demand at finished product level.**
>
> **H2: Products are selected for manufacture under FPp rather than MTO/ETO when they exhibit high volume demand at generic product level.**

Hypothesis H1 was challenged by the study findings. Both demand mix and demand variability were lower - and volume demand was higher - for cables made under FPp compared with those made under MTS. These unexpected findings were the result of unusual circumstances, rather than being a fundamental challenge to the hypothesis. There were two unusual circumstances in this case that influenced the demand profile measures:

- Firstly, the FPp application (unlike MTS) was artificially restricted to one customer which limited the potential for variations in the product and hence demand mix.

- Secondly, in general, cables were only selected for manufacture under FPp when they exhibited volume demand at *end item level* high enough to justify a consignment stock of the polymer used in the postponed sheathing process. Again this limited demand mix and increased volume demand at end item level.

As predicted by H2, the products selected for manufacture under FPp rather than MTO exhibited an average volume demand, at generic level, almost twice that demonstrated by the MTO cables. This was a result of variations in the MTO generic cable specification that did not exist in the FPp generic cable.

***What is the impact on customer service of FPp?***

> **H3: FPp considered as an alternative to MTS increases ex-stock availability.**
>
> **H4: FPp considered as an alternative to MTO/ETO reduces order lead-times and increases delivery reliability but introduces demand amplification**

Hypothesis H3 remains untested because it was not possible to measure ex-stock availability for either FPp or MTS approaches.

Hypothesis H4 was fully tested but only partially supported by the findings. Demand amplification was measured at a weekly level for FPp and MTO orders but it was not detected for either approach. However, cables subject to FPp were demanded on a daily basis, rather than a weekly basis, and at this level demand amplification was detected for the FPp orders. Unexpectedly amplification was detected at the order-driven sheathing process, as well as the stock-driven processes (albeit to a lesser extent). This resulted from the long weekly planning cycle, which created the opportunity to batch similar customer orders together. These findings support hypothesis H4 showing that applying FPp introduced a degree of demand amplification which did not exist for the MTO approach.

The actual order lead-time achieved by FPp was just under half of the order lead-time achieved by MTO supporting hypothesis H4. As expected this was in part because the laid-up cable was manufactured speculatively to stock rather than to order. However the synchronisation of the weekly manufacturing planning process at TB's and VP's factories also contributed to the reduction in order lead-time.

Contrary to the predictions made in hypothesis H4 delivery reliability achieved by FPp was lower - rather than higher - than that achieved by MTO. Only 51% of FPp orders compared to 76% of MTO orders were available OTIF. The reduced delivery reliability under FPp was largely accounted for by 20% of orders that were only partially available on the due date. Two possible explanations were advanced for the poor delivery reliability exhibited by FPp: a lack of postponed sheathing capacity (as suggested by the excess capacity measure in hypothesis H6); and insufficient generic cable stock. Though these fundamental factors no doubt contributed to the poor delivery reliability it appeared that the *underlying* cause was the unusual circumstances of this case. In particular VP (the customer of all cables subject to FPp) was allowed to call-off finished cables rather than have them delivered upon completion. Therefore finished cable stock existed which provided a buffer against poor delivery reliability. Had this not been the case TB would have been forced to address the poor deliver reliability and as a result it would have almost certainly been higher.

***What are the product design implications of applying FPp?***

> **H5: Product families subject to FPp will have a higher level of standardisation and modularity than product families subject to MTO/ETO**

Hypothesis H5 was only partially supported by the findings. As predicted, the cables subject to FPp exhibited greater product standardisation than those made under MTO - both in terms of common components and the degree of commonality index. Overall the commonality index for the FPp UoA was two and a half times that for the MTO UoA and it was higher at every level in the BOM. At the lower BOM levels this was due to the use of a single generic laid-up cable for FPp. However at the sheathing and packaging levels (postponed processes) it was due to the restriction of FPp to one customer. This enabled the standardisation of packaging components (such as reels and labels) and limited the range of sheathing compounds.

Contrary to hypothesis H5 all cables, regardless of inventory management policy, exhibited the same high level of modularity. The generic cable as well, as the customising components (such as the sheath coating and packaging), were all highly modular. However, rather than being the result of a deliberate product design initiative, modularity was an incidental characteristic of the product.

***What are the manufacturing planning and scheduling implications of applying FPp?***

> **H6: Capability of the postponed transformation process to respond to high demand variability requires excess capacity and high throughput efficiency**

Contrary to expected findings, the postponed sheathing process consistently exhibited the least excess capacity - on average less than one third of that present at the stock driven laying up process, which typically exhibited the most. This was not attributable to excessive efficiency losses, as net OEE was very similar and consistent for all processes. Instead, the lack of excess capacity resulted from the provision of less capacity at the postponed process. It was most probable that, rather than being a fundamental challenge to hypothesis H6, this was a result of unusual circumstances at TB. The lack of excess sheathing capacity probably contributed to the poor delivery reliability achieved by FPp which itself challenged hypothesis H4. As previously discussed for hypothesis H4 the existence of finished cable stocks (created by VP's delayed call-offs) provided a buffer against the poor delivery reliability. This allowed the low sheathing capacity to persist unaddressed. Had the finished cable buffer stocks not existed TB would have been forced to address the poor deliver reliability, and probably would have increased sheathing capacity as a result.

It was not possible to measure the throughput efficiency through the postponed process. However, it was possible to conclude that the overall throughput efficiency was reduced by the application of FPp, when compared to MTO, due to the extended time in generic cable stock.

***Production Variety Funnel:*** The number of SKUs at the CODP was greater than the number of finished cable variants demanded – eight SKUs compared to five finished cables. This is contrary to the original conceptual model of FPp which predicted the number of SKUs at the CODP to be substantially less than the number of finished items. Even if FPp had not been restricted to one customer this situation would probably have persisted because sheathing polymers were the main differentiating component - for every new cable variant a new sheathing polymer was likely to be required. Nevertheless locating the CODP at generic cable level (rather than at finished cable level) still provided benefits for TB - the generic cable and sheathing polymers were more flexible than finished cable and certainly of lower value.

## 4.6 CONCLUSIONS

The FPp application at TB was flawed to the extent that after nine months it could no longer be defined as FPp. The finished cable stocks controlled by the customer persisted due to the mismatch between cable supply and demand. This meant that it no longer made sense to maintain a generic cable stock to enable supply on a short lead-time and the order lead-time was extended by one week. As a result of the various flaws in the FPp application many of the hypotheses were challenged. The planning system was too inflexible to support the FPp application without the support of finished cable buffer stocks. The planning lead-time for FPp orders had *not* been reduced compared to that for orders subject to MTO. Instead TB's planning system was synchronised with their customer's system, but this did not take into account the customer's high level of deviation from their manufacturing plan.

The flaws in the FPp application resulted in anomalies in the findings which challenged three hypotheses. The challenge to the demand profile hypothesis (H1) was the combined result of two factors. Firstly the FPp application (unlike MTS) was restricted to one customer. Secondly in general only high volume *end item* cables were selected for FPp to justify a consignment stock of the sheathing polymer. The challenges to the delivery reliability and excess capacity hypotheses (H4 and H6) were attributable to the existence of finished cable stocks which themselves were attributable to the mismatch between supply and demand (the customer delayed call-offs). The finished cable stocks provided a buffer against poor delivery reliability and allowed the lack of postponed sheathing capacity to go unnoticed.

The product modularity findings fundamentally challenged the hypothesis – these findings were not influenced by flaws in the FPp application. Contrary to predictions product modularity was not related to the inventory management policy. All the cables demonstrated very high levels of modularity which were incidental to the product rather than being the result of a deliberate product design initiative.

# CHAPTER FIVE

# 5 Study at Brook Crompton

The study at Brook Crompton was particularly challenging due to the relatively complex nature of the product - the Large Direct Current motors frequently required in excess of 200 distinct components. Moreover the variety was such that over the one year study period less than two motors (on average) were demanded in each variant. In addition orders for motors manufactured under FPp were processed, scheduled and even fulfilled largely outside the existing systems complicating the study further.

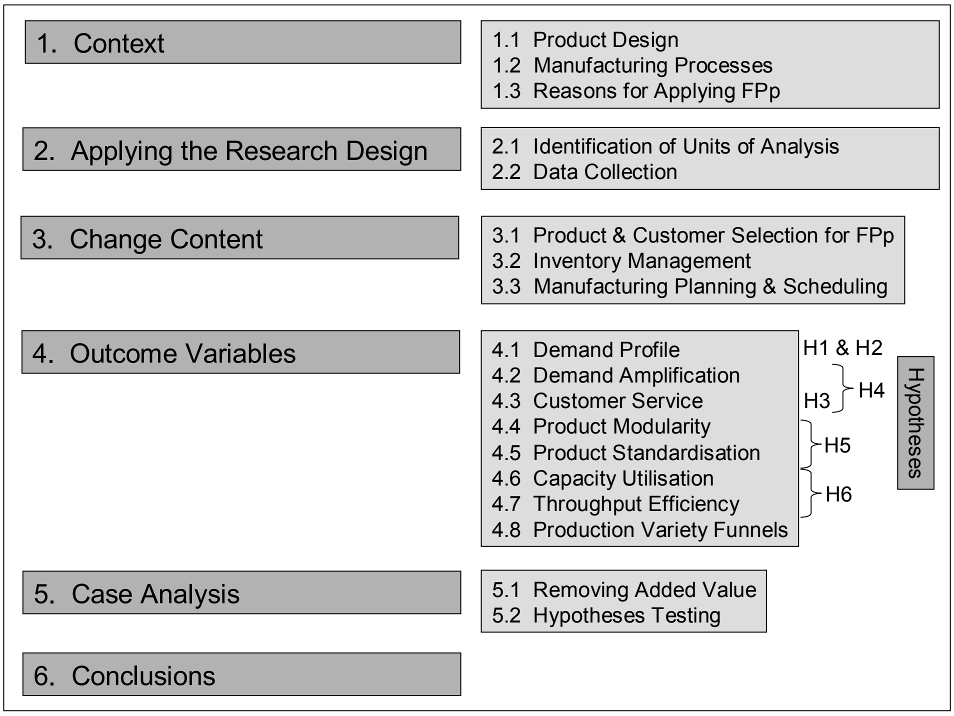



**Figure 5.1: Diagram illustrating the structure of the case study chapters**

In common with the other case study chapters this is structured according to the diagram in Figure 5.1. The contextual features relating to FPp are presented in the first part which includes descriptions of the products subject to FPp, the manufacturing processes used to make them and the reasons for applying FPp. The key aspects of how the research design was applied in this specific study are described in the second part. The ‘change content’ when FPp was applied in a previously MTO and MTS environment is described in the third section. This includes selection of products and customers for FPp, changes to inventory management and manufacturing planning. In the fourth section the ‘outcome variables’, which are the quantitative concepts tested in the hypotheses, are presented. The case analysis is presented in the fifth section which includes an evaluation of the major flaws in the FPp application and testing of the hypotheses against the findings. The chapter closes with conclusions from the study.

## 5.1 CONTEXT

Brook Crompton was Britain’s largest manufacturer of industrial electrical motors and a leading manufacturer of electric motors world-wide. In 2002 Invensys sold Brook Crompton to the Lindeteves-Jacoberg (L-J) Group, an international group of companies focused on motor production. Brook Crompton made over one million motors per year and were the largest single company in the L-J group, which also included Schorch of Germany and Australian manufacturer Western Electric.

Brook Crompton manufactured a wide range of motors from small alternating current (AC) motors to large direct current (LDC) motors. The motors were employed in a diverse range of industrial applications, such as mining, water treatment, paper mills and manufacturing to name a few. At the time of the study Brook Crompton occupied three sites in the UK: Guiseley (Leeds); Blackheath (West Midlands); and Huddersfield. However, the Huddersfield site had recently ceased to manufacture and was the UK distribution centre.

The LDC motors manufactured at the Blackheath site were the focus of this study. Demanded in exceptionally high variety the LDC motors had been manufactured using the FPp approach for many years. The LDC manufacturing capability was moved from the Bull Electric plant at Ipswich to Brook Crompton, Blackheath (BC) towards the end of 1999. By 2002 the LDC motors accounted for approximately half of the £17 million turnover at BC.

### *5.1.1 Product Design*

The LDC motor comprised a central shaft upon which two main cylindrical components were assembled as illustrated in the cross sectional drawing in Figure 5.2. The commutator was made up of copper radial segments interleaved with mica (an insulation material) and was mounted at the non-drive end of the shaft - hereafter called the commutator end (CE). The armature core made up of cross-sectional laminations was mounted at the drive end (DE). The resulting assembly was called the 'unwound armature'. Crucially a copper wire called the armature coil, which carried the electric current, was wound round the armature core, which became the 'wound armature' assembly.

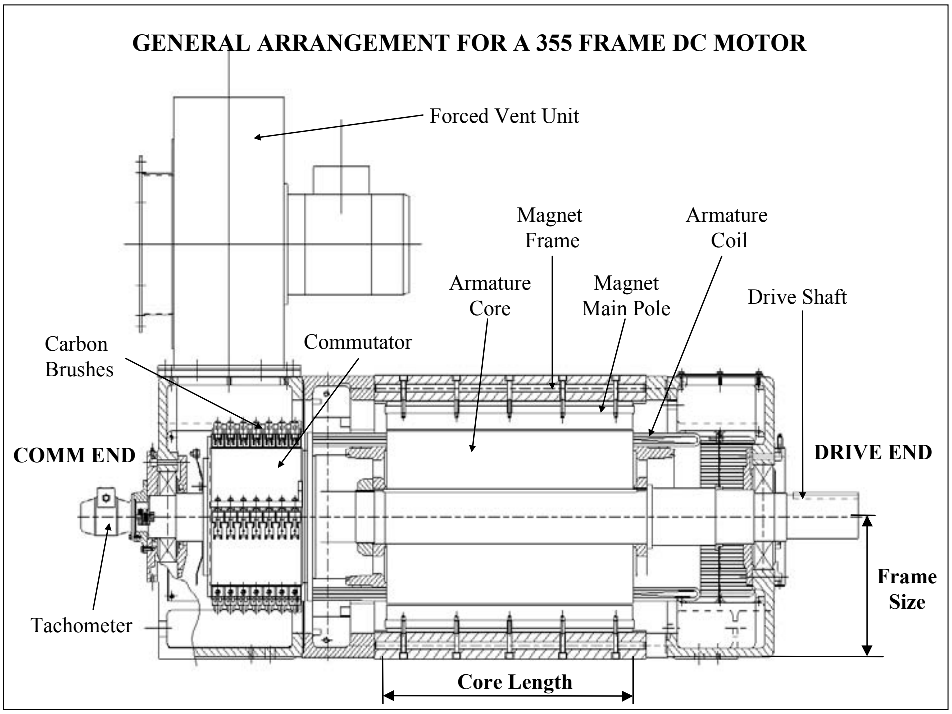



**Figure 5.2: Cross-sectional drawing of a large DC motor showing major components**

The complete wound armature assembly rotated at variable speed within a housing. The commutator rotated within the brush box making contact with a set of carbon brushes through which passed the electric current. The armature core rotated within the magnet body assembly, which consisted of four main poles and four interpoles mounted on a magnet frame. Each of the poles was essentially a copper wire wound on a spool, called the pole winding, mounted on a mechanical assembly.

Typically a motor was specified in terms of its frame size, armature core length, voltage supply, power output (kW) and maximum speed required. The frame size (the centre height of the drive shaft) and the armature core length (shown in Figure 5.2) were used by the factory to categorise the motors.

The application of FPp required that thirty UK standard motors were made-to-stock and subsequently modified to specific customer orders (refer to Appendix 12 for modification details). The modifications commonly involved peripheral components such as tachometers mounted on the shaft, forced vent units or mounting brackets. However just over one third of the motors modified also required far more invasive modifications requiring a change to the magnet components (as detailed in Appendix 12). Although the peripheral components generated significant variety much of the variety in the LDC motors was generated from the magnet body and armature assembly specifications. This is analysed fully in section 5.4.5 on product standardisation and illustrated by the production variety funnels in section 5.4.8.

### *5.1.2 Manufacturing Processes*

The flow process chart in Table 5.1 generally applied to motor manufacture in the LDC area of the factory. The chart describes the main process flow from the manufacture of the commutator to the final assembly of the motor. It also shows the process flow for the manufacture of the magnet body assembly - shown separately since it is conducted in parallel with the manufacture of the armature.

Manufacture of the motor began with the commutator. The coppers and mica adhesive coated laminates were assembled radially and then put through a pressure-oven cycle until they were the right dimension. After this the commutator was machined smooth, fully assembled and grooves machined in the copper laminate sections for wire.

The armature core was built up from cross sectional laminates, a key way cut, then the shaft was pressed into the armature core. The commutator - together with various other components designed to hold the commutator and armature in place - were assembled onto the shaft to make the ‘unwound armature’ assembly.

The armature coil was prepared and wound via a lengthy manual operation onto the armature core. The armature was then electrically tested, the coil connections soldered on an automatic rotating machine, and finally the armature was insulated and re-tested. The re-test triggered the assembly of the poles into the magnet frame to ensure that the magnet body was ready for final assembly upon completion of the armature.

**Table 5.1: A flow process chart for LDC area**

| ***Process Description*** | ***Symbols*** | | | |
|---|---|---|---|---|
| ***Main process flow incl. Armature Manufacture*** | | | | |
| **Manufacture commutator > SLIT COMM.** | ● | □ | ⇨ | ▽ |
| Store commutators. | ○ | □ | ⇨ | ▼ |
| **Build armature core** | ● | □ | ⇨ | ▽ |
| **Armature core, comm. and other components assembled on shaft > UNWOUND ARMATURE** | ● | □ | ⇨ | ▽ |
| Move armature assy. to winding trolleys | ○ | □ | ➡ | ▽ |
| **Wind armature coil onto core** | ● | □ | ⇨ | ▽ |
| **Electrically test armature** | ○ | ■ | ⇨ | ▽ |
| **Solder and insulate armature** | ● | □ | ⇨ | ▽ |
| **Electrically test armature (triggers magnet pole-up) > TESTED WOUND ARMATURE** | ○ | ■ | ⇨ | ▽ |
| Move armature assy. to impregnation area | ○ | □ | ➡ | ▽ |
| **Impregnate armature assy.** | ● | □ | ⇨ | ▽ |
| Move armature assy. to armature finishing area | ○ | □ | ➡ | ▽ |
| **Paint armature and machine comm. mica** | ● | □ | ⇨ | ▽ |
| **Balance armature > FINISHED ARMATURE** | ● | □ | ⇨ | ▽ |
| Move armature assy. to final assy area | ○ | □ | ➡ | ▽ |
| **Assemble motor** | ● | □ | ⇨ | ▽ |
| **Test motor** | ○ | ■ | ⇨ | ▽ |
| **Spray paint motor > FINISHED MOTOR** | ● | □ | ⇨ | ▽ |
| Move finished motor to warehouse | ○ | □ | ➡ | ▽ |
| ***Magnet Body Manufacture*** | | | | |
| **Prepare pole windings** | ● | □ | ⇨ | ▽ |
| **Pole up magnet and assemble magnet body** | ● | □ | ⇨ | ▽ |
| **Prepare compensated winding (frames 280 & 355)** | ● | □ | ⇨ | ▽ |
| **Connect compensated winding (frames 280 & 355)** | ● | □ | ⇨ | ▽ |
| **Impregnate magnet body assy. > MAGNET BODY** | ● | □ | ⇨ | ▽ |
| **Operation** | ● | | | |
| **Inspection** | | ■ | | |
| **Transport** | | | ➡ | |
| **Storage** | | | | ▼ |

Following the successful completion of the electrical tests the armature was impregnated with resin by repeating a lengthy dipping-oven cycle. The armature was then painted (to repel the carbon fibres from the brushes) and the mica machined away so the brushes could make contact with the copper. The armature assembly was then balanced in rotation to give the 'armature' assembly.

Finally the armature, magnet body and numerous peripheral components were assembled in an enclosure. The complete motor – regardless of whether it was made to a customer order or to UK stock - was then fully tested, sprayed with two coats of paint and transported to the finished goods warehouse.

UK standard motors to be modified under the FPp approach were taken from stock and modified, not on the LDC section, but in the Service and Repairs (S&R) section. The modifications varied greatly from the simple change of a data plate taking 10 minutes to the change of a magnet pole involving a motor strip-down and taking up to 3 working days (as detailed in Appendix 12). Further, depending upon the modification the motor sometimes required re-testing and re-spraying.

### *5.1.3 Reasons for Applying Form Postponement*

The reason for applying FPp (and how it was applied) was the subject of interviews with three different informants. The informants were selected because of their close involvement with the relocation of LDC manufacture to BC, and their knowledge regarding the wider issues surrounding the FPp approach. The informants were the Production Engineering Manager, LDC Product Manager and DC Sales Manager. Each informant was asked:

> ***Why was FPp applied - what were the drivers?***

The industrial LDC motors had been manufactured using the FPp approach at the Bull Electric factory for many years. BC continued to use FPp when LDC motor manufacture was transferred to BC at the beginning of the year 2000. All informants testified that LDC motors were subject to FPp in order to provide a more responsive supply than the manufacturing lead-time would otherwise allow. The need to be more responsive was attributed to the type of market the LDC motors were supplied to - the motor replacement market.

The DC Sales Manager had a long history with this particular range of LDC motors - employed as a Design Engineer when they were originated back in the 1970s - he had a unique and highly informed perspective. He described the industrial LDC motor as a 'sunset' product and explained that:

> *'for around the last 15 years the LDC motor has been generally supplied as a motor replacement, rather than a motor for new installations. The AC motor technology has advanced and now tends to be the preferred solution for new installations. At BC we only supply four companies with LDC motors for new installations in the UK. Whereas the motor replacement market is very large with thousands of LDC motors in use and - due to their long life expectancy - it is expected to remain so for many years.'*

According to the DC Sales Manager the order winner for standard LDC motors was 'availability on a short lead-time'. He elaborated:

> *'the motor replacement market is not price sensitive and quality is no longer an order winner. Quite often the existing motor, requiring replacement, is no longer reliable, and should it breakdown the subsequent downtime is likely to be worth many times the motor's value.'*

Although the motors were sometimes supplied to distributors, even these customers required a short lead-time since the motor's high value deterred stock keeping. The DC Sales Manager concluded:

> *'the current BC standard quoted lead-time of 10-14 weeks is satisfactory for special motors, as the sales testify. However, when the motor is based on a standard specification, the UK customers expect a 3-4 week lead-time, which BC has found can be achieved using the FPp approach.'*

The customer service measures endorsed this claim and - on average the motors manufactured using the FPp approach achieved a 3 week lead-time.

## 5.2 APPLYING THE RESEARCH DESIGN

The identification of the units of analysis and the various issues concerned with data collection are addressed in this section.

### *5.2.1 Identification of Units of Analysis*

The main manufacture and assembly of the motor took place in the LDC section with the machine shop making a few individual components. Therefore, the machine shop was outside the scope of this study which was confined to the LDC section and S&R where the modifications took place.

Two types of LDC motors were manufactured: the industrial motors, a proportion of which were subject to FPp (whilst the rest were either MTS, MTO or ETO); and elevator motors which were all MTO or ETO. Considering that the elevator motors were a completely different design to the industrial motors (circular in cross section rather than square), and it was the industrial motors that were manufactured using the FPp approach the elevator motors were excluded from the study.

**Table 5.2: Industrial LDC motors due for despatch between 01/07/01 and 30/06/02**

| Frame Size (mm) | ETO (Contract Motors) | | FPp (Modified UK Stock) | MTS (Direct Sale UK Stock) | TOTAL |
|---|---|---|---|---|---|
| | UK motors | US motors | | | |
| **132** | 36 | 2 | 8 | 2 | ***50 (14%)*** |
| **160** | 34 | 10 | 13 | 2 | ***64 (18%)*** |
| **180** | 26 | 7 | 13 | 3 | ***54 (16%)*** |
| **200** | 30 | 7 | 7 | 7 | ***58 (17%)*** |
| **225** | 26 | 2 | 13 | 3 | ***55 (16%)*** |
| **250** | 8 | 10 | 5 | 4 | ***28 (8%)*** |
| **280** | 6 | 12 | 3 | 3 | ***26 (7%)*** |
| **355** | 13 | 0 | 0 | 0 | ***13 (4%)*** |
| **TOTAL** | ***179 (51%)*** | ***50 (14%)*** | ***62 (18%)*** | ***24 (7%)*** | ***348*** |

**Note: The US standard motors made to the remote stock in the USA are excluded from this table and constituted 9% by volume**

Each unit of analysis (UoA) was based around a *product family* subject to a particular *inventory management policy* and included the respective customer orders due for delivery within a *certain time frame.* Considering the time frame first, the manufacture of the LDC motors was transferred from the Bull Electric, Ipswich factory to BC at the beginning of the year 2000. Production records showed that for more than a year manufacturing at Blackheath was subject to a considerable backlog generated during the transfer. Further, even when production had settled, relatively low volumes of the industrial LDC motors were manufactured (as illustrated in Table 5.2). There was a need to study a reasonable number of orders, such that the measures would achieve an acceptable degree of statistical significance. In consideration of these factors the most recent 12-month period, for which records were available (1st July '01 to 30th June '02) was the identified study period.

The manufacture of the industrial LDC motors was split between four different inventory management policies, depending on the motor specification:

- Contract motors were engineered to order (ETO)
- Modified UK stock motors were form postponed (FPp)
- UK stock motors were made to stock (MTS)
- US standard motors were made to remote stock

These four product groups were used for the UoA, however only three are presented here. The US standard motors were excluded from the thesis, because they could not be satisfactorily classified as MTO or MTS, and only served to confuse the analysis of the different inventory management policies. They were manufactured in a range of US standard designs exclusively for Brook Incorporated USA, who maintain a stock of these motors in the USA and modify them if required. Although classed as MTO by BC (because their manufacture was covered by an order), they were effectively made-to-remote-stock, since they were destined to replenish the USA stock. This was evident from the very small range of variants manufactured - 14 in total - and the comparatively high volumes.

In view of the relatively low demand for industrial LDC motors the UoAs were *not* restricted to particular frame sizes but rather spanned the whole range. Therefore the three product groups shown in Table 5.2 and the associated orders due for despatch during the selected one-year period were studied.

The majority of LDC motors (65%) were ETO and the bulk of these motors were made to metric dimensions and therefore termed 'UK motors'. The 'US motors' were basically metric motors with an imperial frame size, which dictated that a small proportion of the motor's component parts were in imperial sizes.

The second largest product group were modified UK stock motors. These were the UK standard motors made-to-stock and subsequently modified to specific customer orders in accordance with the FPp approach. This UoA was further subdivided for the purpose of certain measures (demand amplification, customer service and throughput efficiency), since around a third of the motors were modified in production rather than from stock (as explained in sections 5.3.2 and 5.3.3).

The final, and smallest division of products, were the UK stock motors sold ex-stock without any modifications and these will form the MTS UoA.

### *5.2.2 Data Collection*

In order to study a sufficient number of customer orders it was necessary to study a one year period as argued in the previous section. Insufficient time was available to conduct a real time one-year study therefore - considering the plentiful historical data available - a retrospective study was conducted. The majority of the data collected applied to the period between 1st July '01 and 30th June '02 and the study was conducted between July and October 2002.

A retrospective study can raise questions regarding the *reliability* of the data. Interview data naturally required support from documentary or database evidence, and fortunately all the interviewees were not only still employed at the factory, but in the same roles, as for the study period. Fortunately, therefore all the informants had first hand experience and knowledge of the time period in question.

A good source of evidence for customer service and demand profile *measures* was the Order Log access database. This was automatically updated on a nightly basis with factory order progress data, including despatch dates, originating from the MRP system, JBA. Unfortunately the MRP operation booking dates were found to be unreliable because the Planner did not use the MRP system to monitor job progress. Instead she preferred to use a purpose designed Excel spreadsheet named the ‘LDC Tracker’ (as explained in section 5.3.3.). Therefore for the purpose of measuring demand amplification and throughput efficiency the MRP booking dates were corroborated by dates on the Excel LDC Tracking spreadsheet. With regards to general reliability the data retrieved from the MRP system and the ‘LDC Tracker’ was no less reliable or accessible during the study than when it was generated.

The retrospective nature of the study did have one draw back the data was not available to measure ex-stock availability in terms of the proportion of enquiries for which the correct UK stock motor was available. However, two alternative sources of data were available which gave a good indication of the ex-stock availability measure for both the motors subject to FPp and MTS.

Overall the reliability and completeness of the data were only marginally affected by the retrospective nature of the study.

## 5.3 CHANGE CONTENT

In this section the changes required to apply FPp in a MTS and MTO environment are described including: product and customer selection, inventory management and manufacturing planning and scheduling changes.

### *5.3.1 Product and Customer Selection for Form Postponement*

In common with ‘the reasons for applying FPp’, how products and customers were selected for FPp was the subject of interviews with three different informants (previously listed in section 5.1.3). The two questions asked of all informants, and their collective answers, are presented below:

> ***Was the ‘stock modification’ (FPp) approach limited to certain customers, and if so why?***

No. Stock modifications were carried out for any customer that required a standard UK stock motor with modifications.

***Was the 'stock modification' (FPp) approach limited to certain motor specifications, and if so why?***

Yes, the stock modification approach was limited to 30 recognised standard UK motor specifications, each demanded by multiple customers. Bull Electric at Ipswich selected these motors (prior to the relocation of LDC motor manufacture to BC) therefore it was not possible to confirm *how* the selection was made.

It was possible that these motor specifications were selected for the FPp application by volume demand. However during the study period 4 of the 30 UK stock motors were not subjected to demand and the demand on the remainder accounted for 52% (86 motors) of the UK specification motors ordered (the others were ETO). The DC Sales Manager believed that the range of standard UK motors stocked should have covered all combinations of the standard frame sizes, core lengths and wiring specifications totalling 66 motor specifications. He argued that 'Brook Crompton is not competitive on lead-time for many of the standard UK motors and sales are lost as a result'. He continues:

> *'the LDC motor was designed to be stocked in component form as far back as the armature laminates when they are more flexible. If this were the case for the full range of standard motors the stock levels required would be no higher than the current levels required to support the 30 motor specifications.'*

This argument was supported by evidence showing that many components exhibited commonality across the standard motors. The degree of commonality index showed that on average distinct components (within the armature assembly and magnet body of generic stock motors) are common across 10% of the 30 motor specifications.

### *5.3.2 Inventory management*

Inventory management encompassed order processing and the subsequent control of motor stocks, both generic and finished. Also considered in this section – and inherent in the inventory management approach - is the Customer Order Decoupling Point (CODP) location. Evidence for inventory management was gathered from interviews with the LDC Sales Co-ordinator, LDC Planner, Product Engineering Manager and

Engineering Systems Manager. It was supported by evidence from the MRP system, JBA, which ran overnight, every night.

Two flow charts illustrating the order processing and stock control procedures can be found in Appendix 12. The first chart applies to the thirty UK stock motors which were sold ex-stock (MTS) or modified under the FPp approach. The second chart applies to 'contract motors' which were partially designed and entirely manufactured to a customer order – in other words engineered-to-order (ETO). Table 5.3 summarises the key features of the three inventory management approaches.

**Table 5.3: The main features of the inventory management policies compared for the three UoA.**

| *Features* | *ETO (Contract Motors)* | *FPp (Modified UK Stock Motor)* | *MTS (Direct Sale UK Stock Motor)* |
|---|---|---|---|
| ***Standard quoted leadtime*** | 10 – 14 wks (depending on frame size) | 1 – 4 weeks (depending on modification, parts availability and stock motor availability) | Next day (depending on stock motor availability) |
| ***Engineering input*** | Electrical and Mechanical | Normally only electrical | None |
| ***Components for order-driven processes*** | Wide range of components | 30 UK standard motors and various components | n/a |
| ***Components supply*** | | Standard UK motors…. replenishment orders placed on MPS by MRP when stock fell below target. LDC Planner controlled order release. | |
| | Components… made in-house, stock replenishment, purchased to order | | n/a |
| ***CODP location*** | Ordering of raw materials | UK stock motors | |

The standard quoted lead-times for the contract motors depended on the frame size of the motor and ranged from 10 weeks for a small motor to 14 weeks for the largest. This included 3 weeks in the Engineering Department for design work.

Customer orders for contract motors were logged onto the MRP Customer Order Module as quotations to ensure material was not allocated to them. Only when the engineering work was completed were the quotations given 'planned' status. During the MRP overnight run material was allocated to the orders and then the orders were available for manufacture on the one week period MPS. The LDC Planner controlled when the orders were released into the factory.

The flow chart for the UK stock motors covers modified stock (FPp) and direct sale stock (MTS). For both cases two eventualities were covered: when stock was available in the warehouse; and when no stock was available but the required motor was in production. The latter case was relatively frequent because motor stocks were maintained at only 50-70% of target. In the case of modified stock motors around a third of motors were modified in production.

The quoted lead-time for stock motors (modified or direct sale) depended on their availability or status in production. In addition the lead-time for modified motors was dependant on the modification itself and part availability. However it was questionable whether the salesmen did check part availability prior to providing a quote.

Although the UK motor stock levels were monitored by the LDC Planner the target levels had not been reviewed or changed since LDC motor production was transferred from Bull Electric (Ipswich) to BC at the beginning of 2000. The MRP system automatically generated a stock replenishment order during its overnight run as soon as the stock levels fell below target. However, the LDC Planner controlled order release (timing and quantity), and thereby controlled the stock levels. The LDC Product Manager admitted that it was very difficult to control the stock levels as sales were so erratic. This was compounded by the high value of the motors - a strong deterrent against stock build-up. Consequently the LDC Planner was restricted to a replenishment quantity of one motor. The interviews with the Planner and Product Manager suggested that stock motors were manufactured whenever capacity existed over and above that required to manufacture the contract motors.

For contract motors the entire motor manufacture was driven by a customer order, and indeed the purchase of many of the raw materials, therefore the CODP was located at raw material ordering. In contrast the entire manufacture of the UK stock motors was stock driven, therefore in the case of the direct sale motors the CODP was at the finished motor. Whereas, the modifications were driven by customer orders, therefore the CODP for modified motors was at the standard motor. However, should the motor be modified in production, the CODP was located at the point in manufacturing where the motor was allocated to the order, and therefore variable.

The factory orders for stock modifications largely by-passed the MRP system as illustrated by the flow chart in Appendix 12. The Order Processing Department (OPD) advised either the warehouse or the LDC section (depending on the motor availability) that the motor required modification. Further, OPD ensured the modification instructions were sent to the section which would perform the modifications. The only 'knowledge' the MRP system had of a stock modification order was the requirement of a UK stock motor. Consequently the MRP system was not able to provide OPD with progress data only a despatch date.

### *5.3.3 Manufacturing Planning and Scheduling*

Manufacturing planning and scheduling covers the process from the orders being present on the MPS to the jobs being scheduled and monitored through the operations. Evidence was gathered from interviews with the LDC Planner, the LDC Product Manager, Customer Service & Warranty Officer and the After Sales Service Manager. The latter two informants had involvement with the stock modifications only.

Whether the motors were ETO or MTS made little difference to the way the LDC section planned and scheduled production as illustrated by the flow chart in Appendix 12. With the exception that motors covered by a customer order (contract motors) were given priority throughout their production.

The main features of manufacturing planning are compared for the MTO, MTS and FPp approaches in Table 5.4. The LDC Planner scrutinised the orders daily on the one week period MPS and released them on the basis of raw material availability, capacity availability and the due date. A limit of 25 motors per week (based on the armature impregnation capacity) had been placed on the number of LDC motors launched. This was broken down by frame size based solely on the tooling available for commutator and armature building - not a true reflection of capacity.

The LDC Planner raised the Works Orders for the parts to be manufactured in the machine shop and on the LDC section (commutator, armature core, etc). The MRP system provided a booking-off facility for monitoring job progress. However no terminals were present on the shop-floor, and the LDC Planner and Product Manager believed that the booking points were insufficient to monitor and control material flow. Instead the LDC Planner 'religiously' used an Excel spreadsheet called the LDC Tracker (designed by the LDC team) for this purpose.

**Table 5.4: Main features of manufacturing planning compared for MTO, MTS and FPp.**

| *Features* | *MTS (UK Stock Motors* | *ETO (Contract Motors)* | *FPp (Modified UK Stock Motor)* |
|---|---|---|---|
| ***Manufacturing orders*** | Processed by MRP system driven by one week period MPS | | By-passed MRP system |
| ***Customer orders entered onto SOB*** | Any time | | |
| ***Release manufacturing orders to shopfloor*** | Daily | | Any time |
| ***Order Processing and Manufacturing Planning Lead-time*** | Approximately 0.5 hour for order processing | 4 weeks (incl. 3 weeks allowed for engineering) | 1 – 3 days |

The LDC Planner issued Works Orders to operations in one-week batches. The Operator sequenced the jobs and if the opportunity arose batched jobs of the same frame size together to reduce changeovers. The Operator completed daily booking sheets which the LDC Planner used to update the Tracker.

Manufacturing planning for stock modifications (FPp orders) was conducted outside the MRP system as illustrated by the flow chart in Appendix 12. It had not been possible to set-up the MRP system to process the extremely varied modifications due to the lack of flexibility in the BOMs. The stock modifications were normally carried out in S&R. Upon receipt of the stock modification instructions the Service Manager checked part availability and raised purchase requisitions. In the event that the parts were made, either in the machine shop or on the LDC section the LDC Planner raised works orders and controlled their delivery. This was not uncommon 12 of the 60 stock motor modifications studied required parts made on the LDC section (pole coil or a pole bore), and a further 5 modifications required parts made on the machine shop.

The Service Manager cited:

> *'the acquiring of parts for stock modifications to be the main problem. Whereas the LDC section was supplied via Kanbans or kits from stores, stock modifications were not, they were treated as a hindrance, although they were still a sale'.*

S&R transported the motor from the warehouse and picked all the bought-in parts from stores. Clearly the whole process of acquiring parts for stock modifications was very inefficient and entirely manual to the extent that even the purchase requisitions were hand written.

S&R order priorities were agreed at the Weekly S&R Planning Meeting, attended by both the Warranty Officer and the Service Manager. Stock modifications were treated like service and repair jobs and given priority on the basis of the due date.

About one third of stock modifications studied were performed by the LDC section on UK stock motors in production. Upon receipt of the stock modification instruction sheet the LDC Planner allocated the motor to the order and changed the materials requirements in the MRP system accordingly. Thereafter the motor was scheduled and monitored through the LDC section as previously described.

The LDC section approach to controlling stock modifications was more efficient than the S&R approach in part because material acquisition and control was conducted within the MRP system. However, once a motor was released and materials allocated to the order it was not easy for the LDC Planner to change material requirements (the MRP system was not designed to be flexible in this way). It required careful manipulation of the JBA system to ensure that stock records remain accurate.

## 5.4 OUTCOME VARIABLES

The measures taken will be presented and compared for the three UoAs over the following eight sub-sections. The first section presents the demand profile measures, demand volume, mix and variability. In the second section the demand amplification plots are discussed. The customer service measures including ex-stock availability, order lead-time and delivery reliability are analysed in the third section. The fourth and fifth sections address product modularity and standardisation. Capacity utilisation measures and throughput efficiency measures are presented in the next two sections and finally the production variety funnels are compared.

### *5.4.1 Demand Profile*

Evidence for the three demand measures was gathered from the Order Log Access database, onto which all customer orders were logged upon receipt. It was important for measuring demand variability (and amplification) that the demand placed on the manufacturing system by both domestic, and export, orders was measured in the same time frame. Therefore the acknowledged due date (effectively the ex-works due date) was taken as the due date for all orders with the proviso that for export there was a transit time (refer to Appendix 13 for a detailed explanation).

**Table 5.5: The demand measures compared for the UoA**

| *Measure* | *ETO (Contract Motors)* | *FPp (Modified UK Stock)* | *MTS (Direct sale UK Stock)* |
|---|---|---|---|
| ***No. of orders*** | 169 orders | 59 | 23 orders |
| ***Demand mix at end item level (generic level)*** | 155 variants (155 variants) | 56 variants (24 variants) | 14 variants (14 variants) |
| ***Total volume demand*** | 229 motors | 62 motors | 23 motors |
| ***Average volume demand at end item level (generic level)*** | 1.5 motors (1.5 motors) | 1.1 motors (2.6 motors) | 1.6 motors (1.6 motors) |
| ***Average CV of demand at end item level*** | 343% (148-346%) | 341% (234-346%) | 292% (181-346%) |
| ***Average CV of demand at generic level*** | 343% (148-346%) | 235% (124-346%) | 292% (181-346%) |

The demand measures for the UoA are summarised in Table 5.5. For the full statement of demand for all motors in the UoA refer to Appendix 13. The CV of demand was calculated from the monthly demands over the one year study period.

Both the ETO and FPp motors had a very high demand mix in relation to the volume demand. There were few repeat orders - only 11 out of the 155 ETO variants and 3 out of the 24 FPp variants were subject to more than one order. Further all repeat orders were limited to the initial customer. However, although the demand mix (and number of repeat orders) appeared to be in the same category for all these motors, the motors subject to FPp were not customised to the same extent as the ETO motors. Just over a quarter of the FPp motor variants (16 out of 56) were UK stock motors with merely a customised dataplate added (refer to section 5.4.5 for more details).

As predicted the demand mix for the MTS motors was less than those subject to FPp. In fact only 14 of the 30 UK stock motors were sold ex-stock (MTS). Further the average volume demand at finished motor level was the lowest for those motors subject to FPp - an indication of the great variety in these finished motors.

The average volume demand at the generic motor level was highest for the FPp motors. For the ETO motors, the variety in the generic motors (which was indicated by the armature assembly specifications) was the same as the variety at the finished motor level. Therefore the volume demand at generic level was no higher than at finished motor level.

The demand variability was very high for all UoA reflecting the high variety-low volume at end item level. Even at the generic UK stock motor level demand was very variable at 235% CV. To ensure high ex-stock availability a high safety stock would have been required – this was discouraged because of the high value of the motors.

It should be noted that 346% variability which features as the upper bound for all three UoA represents the situation where only one motor of a particular variant was demanded over the whole year. As you might expect this was a very common occurrence particularly for the ETO motors, and FPp motors, both of which exhibited the highest demand variability.

Overall the demand analysis showed that the industrial LDC motors were required in extremely high variety in relatively low volumes. In total a volume of 347 motors were ordered in 238 variants, an average of 1.5 motors per variant. Two-thirds (229) of these motors were manufactured as contract motors (ETO).

Summary: the industrial LDC motors in general were required in extremely high variety and relatively low volumes, resulting in very high demand variability. The demand mix for the motors manufactured under FPp was four times higher than that for the MTS motors, 56 compared to 14 variants. As a result the demand variability at finished motor level was higher for the FPp motors at 341% compared to 292% for those motors MTS. The average volume demand for finished motors was lower for the FPp motors than for the MTS motors, 1.1 compared to 1.6 motors. Finally the average volume demand at generic motor level for the FPp motors, was higher than that demonstrated by the ETO motors 2.6 compared to 1.5 motors.

### *5.4.2 Demand Amplification*

The demand data presented in the previous section was used to measure the demand imposed on the manufacturing system. The manufacturing orders were the motor works orders released into the factory as recorded on the LDC Tracker sheet.

The manufacturing schedules were not retrospectively available. However jobs were sequenced on each work station on a daily basis by the operator and 'booked off' upon completion by the LDC Planner on the LDC Tracker sheet. Further only one motor was produced under each works order. Therefore the operation booking off dates were within a day or two of the scheduled output dates and accurately represented the scheduled sequence of jobs at each process and therefore the batching - important to show demand amplification.

The demand amplification charts for the ETO and MTS UoA are shown in Appendix 14. The plots in each chart span the same weekly time buckets and use the same scale so the relative amplitude of demand can be easily compared. Each chart shows: the weekly demand for the motors (due between 1 July '01 and 30 April '02); the motor works orders released; and the manufacturing schedules for the finished commutator, the balanced armature and the finished motors shipped into the warehouse. In this case study illustrating demand at a weekly level was the highest resolution possible because all motor orders were given due weeks rather than due days.

From the production records available it was not possible to split the UK stock motor production between those motors that were subsequently modified (FPp), and those that were sold direct ex-stock (MTS). Therefore, the UK stock motor demand amplification chart in Appendix 14 is for all UK stock motors.

There are no obvious signs of demand amplification for the ETO UoA. Each plot shows peaks and troughs of similar amplitude to those evident on the plot of customer demand. Particularly towards the latter half of the time period analysed the patterns of motors scheduled and works orders released reflects the pattern of demand quite accurately. The patterns on the plots are staggered due to the 6-week manufacturing lead-time required for these motors.

The chart for the UK stock motors showed a degree of demand amplification. The peaks in demand were particularly amplified at the balanced armature schedule and the shipped to warehouse schedule. However the pattern of motors released and the commutator schedule exhibited a lower degree of demand amplification. The obvious peak in motors released around week 33 was probably an effort to boost depleted motor stocks. This explanation was supported by the relatively high level of modifications performed in production between weeks 27 and 33, a scenario which only occurs in the absence of the appropriate stock motors.

It was possible to split the demand for UK stock motors between those that were modified (from stock and in production) and those that were sold ex-stock. Subsequently the demand for modifications satisfied from stock was compared with the S&R modification schedule (effectively the modification completion dates recorded on the LDC Stock Modification Record), as the chart in Appendix 14 illustrates. As expected no demand amplification was evident for the order-driven modifications.

Summary: there were no obvious signs of demand amplification for the ETO UoA. The demand amplification chart for all the UK stock motors (modified and sold ex-stock), showed a degree of demand amplification, particularly at the balanced armature schedule and the shipped to warehouse schedule. The demand for the modified from stock motors was compared with the S&R modification schedule and as expected no demand amplification was evident for the order-driven modifications.

### *5.4.3 Customer Service*

Three measures were used to monitor customer service - order lead-time, delivery performance and ex-stock availability. Unfortunately the hypothesis featuring ex-stock availability pre-supposed that orders subject to FPp and MTS did not pull from the same stock, however in the BC study this was the case. Nevertheless ex-stock availability was measured for the FPp and MTS UoA and details are presented in Appendix 15. It was only possible to measure ex-stock availability in terms of the proportion of orders (rather than orders and enquiries) for which the correct stock motor was available. Consequently this measure ignored the many enquiries which did not translate into orders because the stock motor was not available. However, even using this extremely lenient measure of ex-stock availability only 63% of FPp orders could be satisfied from stock (while the remainder were modified in production). This was in part because the UK motor stock levels were deliberately maintained at only 50% to 70% of the established target level due to their high value and unpredictable, erratic demand.

For the order lead-time and delivery reliability measures it was relevant whether an order was satisfied from stock or production. Clearly, if a motor was in the early stages of production, rather than being available ex-stock a longer lead-time would be required. For this reason the FPp UoA was split into two sub-units those orders satisfied by motors from stock, and those orders satisfied by motors in production.

Neither order lead-time or delivery reliability to the customer were being measured by the factory during the period of the study. To determine these measures both the promised and actual order delivery dates to the customer were required.

The actual delivery dates to the customer were unavailable, however the ex-works dates were available. For export orders the promised ex-works dates were available providing a good measure of delivery reliability. However for domestic orders only promised delivery – rather than promised ex-works dates - were available and the transit time was normally in excess of 24 hours. Therefore the delivery reliability measure was rendered slightly lenient for domestic orders. Refer to Appendix 15 for a detailed explanation of the dates used for the order lead-time and delivery reliability measures.

The promised and actual order lead-times were measured from the receipt of the customer order to the promised delivery and ex-works dates respectively. These measures were made with the proviso that transit times were not taken into account except for on the promised order lead-times for domestic orders.

The evidence for all dates was found on the Order Log. The vast majority of customer orders were for one motor and the largest order due during the study period was for six contract motors. Therefore both the order lead-time and delivery measures were taken for each motor rather than order. The delivery reliability to the customer measure was effectively the proportion of motors despatched *before, or on,* the acknowledged due date. Whereas the delivery reliability into the warehouse was the proportion of motors shipped into the warehouse before, or on, the due into warehouse date (which was one week prior to the acknowledged due date to allow for distribution). The evidence for both these dates was taken from the LDC Tracker sheet.

**Table 5.6: The order lead-time and delivery reliability measures for all UoA.**

| ***Measures*** | ***ETO (Contract Motors)*** | ***FPp (Modified in Production)*** | ***FPp (Modified from Stock)*** | ***MTS (Direct sale UK Stock)*** |
|---|---|---|---|---|
| ***No. of motors assessed*** | 219 | 19 | 35 | 23 |
| ***Av. promised order lead-time*** | 14.2 wks | 2.4 wks | 3.4 wks | 0.2 wks |
| ***Av. actual order lead-time*** | 13.9 wks | 2.6 wks | 3.0 wks | 0.1 wks |
| ***Engineering input?*** | Electrical and Mechanical | Normally only electrical | Normally only electrical | No |
| ***Av. leadtime prior to….*** | 6.6 wks | 0.1 wks | 0.5 wks | N/a |
| | .works order release | ..booking out of engineering | | |
| ***Av. order lead-time measured from…..*** | 7.3 wks | 2.5 wks | | N/a |
| | .works order release | ..booking out of engineering | | |
| ***Delivery Reliability*** | | | | |
| ***Delivery reliability into warehouse*** | 61% | Insufficient data available | 34% | N/a |
| ***Delivery reliability to the customer*** | 63% | 79% | 66% | 96% |
| ***Av. lateness to the customer*** | 1.8 wks | 1.7 wks | 1 wk | N/a |

The order lead-time and delivery reliability measures for each UoA are presented in Table 5.6. The promised and actual order lead-times for the FPp motors were less than a quarter of that for the ETO motors at around 3 weeks. This was due to both a reduction in the lead-time prior to manufacturing and the manufacturing lead-time itself. On average the ETO motors required a 6.6 weeks lead-time prior to the release of the works order into manufacturing compared to a mere 3 or 4 days for FPp motors. The lengthy delay on works order release for ETO motors was due - not only to engineering work - but also the long lead-time on various non-standard bought-in parts (such as the shaft and copper segments for the commutator). The manufacturing lead-time for motors subject to FPp was only one third of that for an ETO motor, 2.5 weeks compared to 7.3 weeks.

The delivery reliability to the customer for ETO motors was 63% compared with 70% for the FPp motors. Curiously, however, the FPp motors were generally shipped to the warehouse later than the contract motors as the delivery reliability into the warehouse measure shows. Only around 34 % of the modified-from-stock motors compared with 61% of the ETO motors were shipped to the warehouse before, or on, the due-into-warehouse date (one week prior to the acknowledged due-to-the-customer date).

The FPp approach only provided a modest improvement in delivery reliability compared to the ETO approach and in general delivery reliability was poor especially when it was considered that the measure was slightly lenient (on domestic orders as discussed). There are a number of possible explanations for the poor delivery performance of FPp:

- Firstly, it was claimed that when a part made in the BC machine shop was required for a stock modification, the required part was not given priority. However only 5 (8%) of the 60 motors subject to FPp required such parts.

- Secondly, the quoted lead-times for the FPp motors did not take into account parts availability, and few bought-in parts required for modifications were stocked. In addition the process of acquiring these parts was very laborious as discussed in section 5.3.3.

- Thirdly, only very limited capacity was available in S&R, this coupled with the fact that S&R was primarily tasked with service and repairs probably resulted in modifications being performed in an unresponsive manner. This is supported by the lower delivery reliability achieved by motors modified from stock (in S&R) compared to those modified in production (66% compared with 79%).

- Finally low standard motor stocks may have contributed to the poor delivery reliability achieved by FPp. However this does not seem to be the case when it is considered that higher delivery reliability was achieved by those motors modified in production than those modified from stock (79% compared to 66%). This suggested that the absence of motor stocks improved delivery reliability.

Comparing the two approaches to FPp, modified in production and modified from stock, the former appears to achieve a shorter actual order lead-time and a significantly higher delivery reliability. The actual order lead-time provided by the modified in production approach was 2.6 weeks compared with 3.0 weeks for modified from stock. The reduction in lead-time appears to be due to the 0.4 weeks reduction in engineering time (see lead-time prior to booking out of engineering) which is a feature of the modification type. Of the modified in production motors 50% involved a data plate re-stamp only (the most trivial modification requiring virtually no engineering time) whereas only 13 % of the modified from stock motors involved such a trivial modification.

This disparity in modification types may also have contributed to the higher delivery reliability achieved by the modified in production approach, 79% compared with only 66% for the modified from stock approach. None of the motors, which received a data plate re-stamp only, whether modified in production or from stock, were delivered late. In short the apparent improved customer service offered by the modified in production approach may be due to the disparity of modification types rather than the operation of the inventory management approach itself.

***Summary:*** the hypothesis on ex-stock availability pre-supposed that orders subject to FPp and MTS did not pull from the same stock, however in the BC study this was the case. The average actual order lead-times for the FPp motors were less than a quarter of that for the ETO motors at around 3 weeks. This was due to both a reduction in engineering and bought-in parts lead-time, and the manufacturing lead-time itself (7.3 to

2.5 weeks). The FPp approach only provided a modest improvement in delivery reliability compared to the ETO approach, 70% compared with 63% respectively. Two possible explanations were offered for this concerning modification parts availability and the limited nature of resources in S&R, where the majority of modifications took place.

### *5.4.4 Product Modularity*

The relative degree of modularity exhibited by the motors in the three UoA was assessed using evidence gathered from interviews with the Product Engineering manager, the Engineering Systems Manager and a Senior Mechanical Engineer. This interview evidence was corroborated by the indented BOMs, a dramatically simplified version of which is illustrated in Figure 5.3.

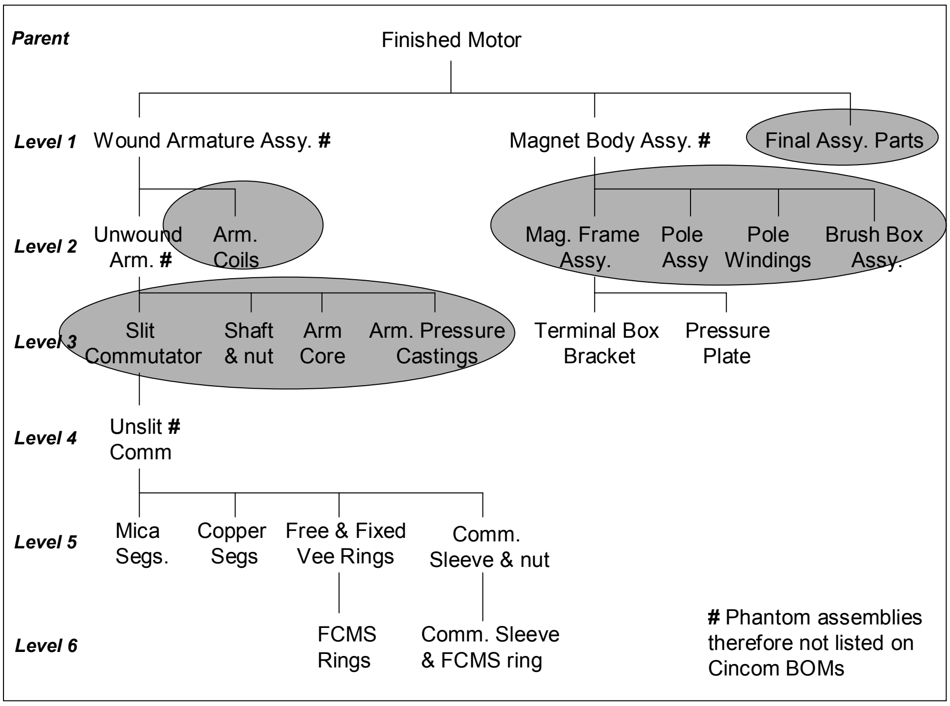



**Figure 5.3: Indented BOM showing only major components at all six levels (shaded areas represent those sections of the BOM detailed on the Cincom BOMs)**

The LDC motor was by far the most complex product studied and the relationship between its functional architecture and physical architecture was not straight forward. Central to the functional specification was the electrical specification covering the voltage supply and the power output. This determined the design of the armature coil, armature core, the magnet pole windings (interpole and main pole), commutator, and the brush ring assembly. It was clear from the previous description of the motors structure (section 5.1.1) and the cross sectional drawing in Figure 5.2 that these components were dispersed round the motor in different major sub-assemblies: the wound armature assembly, the magnet body assembly and the brush box assembly. Therefore the functional electrical element corresponded with numerous physical components dispersed through the motor. This was supported by evidence from the Cincom configurator (a proprietor knowledge based system) which established the physical configuration of the parts in the BOM from the user specification and engineering data. The Cincom BOM was split into sections called 'configuration elements', which grouped together components relating to a particular functional element. One such element was the ‘armature electrical element’, which grouped together the aforementioned (physically dispersed) components relating to it.

From the Cincom BOMs it was evident that many other elements of the functional architecture *did* correspond to particular sub-assemblies or components. Generally these were assembled in the final stages of manufacturing and included *essential* functional elements such as the motor enclosure, temperature protection, and the terminal box. They also included a number of *optional* functional elements such as forced ventilation unit, air pressure switch, brakes, heaters, coolers, and tachometers. Further it appeared that there was little in terms of unwanted interactions between these modules.

Many of the stock motor modifications (35 out of 60) involved only the highly modular final assembly components. However a substantial number (25 out of 60) involved components within the magnet body assembly. Over half of these modifications (14 out of 25) involved a change of thermistors which are separate physical components providing temperature protection and assembled in the magnet body assembly. Therefore just under a quarter of the stock motor modifications (11 out of 60) involved the main magnet pole and brushes which demonstrated a relatively low degree of modularity.

The type of modularity exhibited by the motors was ‘component swapping’ modularity (Pine, 1993). Different components, in this case various peripheral components, were paired with the same basic product, a UK stock motor, to produce variety in the finished product.

***Summary:*** all motors regardless of inventory management policy exhibited the same level of modularity. The major sub-assemblies in the LDC motor exhibited a very low degree of modularity. However peripheral components and sub-assemblies - generally involved in final assembly - did correspond to particular functional elements on a one-to-one basis thereby exhibiting a high degree of modularity. Just over half of the stock modifications involved only the highly modular peripheral components, and a further quarter involved a modular component embedded within the magnet body assembly. Therefore just under a quarter of the stock motor modifications involved components which demonstrated a relatively low degree of modularity.

### *5.4.5 Product Standardisation*

The level of product standardisation was indicated by two measures: the proportion of components common to all variants in the UoA and the degree of commonality index. Initially it was envisaged that the evidence required for the product standardisation measures would be collected from the full indented BOMs on the MRP system. However, these BOMs were unavailable due to system changes. Moreover, the MRP BOMs were not in a standardised format (manually transferred from the Cincom Configurator), which would have hampered the analysis of specific parts across a set of BOMs. In light of this it was decided to use the BOMs generated by the Cincom configurator which are in fact used to populate the MRP BOMs.

The Cincom BOMs had the advantage of being in a standardised format and were also accessible using the Microsoft Excel spreadsheet application. However, they had a number of limitations (refer to Appendix 16 for a full explanation) the most significant of which was that they only covered levels 1, 2 and 3 of the full indented BOM, which had six levels (as illustrated in Figure 5.3). Generally the lower couple of levels from each major sub assembly - wound armature, magnet body and final assembly components - were missing. Fortunately, however these levels covered mainly raw materials for components manufactured by the machine shop, which was not within the scope of this study, therefore these components were not subject to analysis. The only significant exceptions were the missing commutator components on level 5, which were assembled by the LDC section. With consideration to time constraints it was decided that it was necessary to exclude these from the product design measures, however the variety of these components was estimated for the production variety funnel (presented in section 5.4.8).

LDC motors contained many *distinct* or different parts, for instance a 180 frame size UK stock motor required 157 different parts, and a 355 frame contract motor required around 230 different parts. This demonstrated the extent to which the BOM in Figure 5.3 had been simplified. However, many of these parts were trivial raw material parts such as cables and sealing plugs stocked on the production line (90 in the case of the aforementioned UK stock motor) therefore it was necessary to scope the analysis to include only significant parts. Refer to Appendix 16 for full details on the selection of parts and a list of the part types analysed for each UoA. All parts with T* part numbers were analysed because these were the most significant parts and featured in the original LDC motor design. The T* parts included all parts made by BC and many of the MRP purchased parts. In fact wherever possible all MRP purchased parts were included in the analysis.

The components used in the UK stock modifications were not available on the Cincom BOMs instead the Stock Mod Instruction Sheets were the source of this information.

Before considering the product standardisation measures a few basic facts illustrate the difference between the three UoA. The UK stock motors were all supplied with housings offering the standard International Protection level (IP23), were all made to operate at the standard maximum speed and the majority of them require a standard voltage power supply. In contrast the contract motors varied with respect to each of these fundamental characteristics and in addition could be either UK or US motors.

A summary of the product standardisation measures is shown in Table 5.7. The average number of distinct components analysed for each motor was very similar for all three UoA, around 52 components. For any given UoA very few components were found to be common, in fact no components were found to be common across the ETO motors. The roller bearing data plate was common across the FPp and MTS motors and the two thermostats on the magnet body assembly, were common across the MTS motors. None of the major components were common across any of the UoA.

The major components which are those determined by the electrical specification, such as the armature core, the magnet pole windings and the commutator, were subject to tremendous variety especially across the ETO motors. Interestingly the main pole windings were subject to similarly high variety across both the ETO motors and the FPp motors, because the stock modifications included 6 main pole winding changes.

**Table 5.7: Product standardisation measures compared for the UoA**

| ***Measures*** | ***ETO (Contract Motors)*** | ***FPp (Modified UK Stock)*** | ***MTS (Direct sale UK Stock)*** |
|---|---|---|---|
| ***No. of end items (generic level)*** | 155 variants (155) | 56 variants (24) | 14 variants (14) |
| ***Average no. of distinct components analysed per end item (range)*** | 51 (31-65) | 52 (47-58) | 51 (48-52) |
| ***No. of common components*** | 0 | 1 (2%) | 5 (10%) |
| ***Degree of Commonality Index*** | | | |
| ***BOM Level 1 components in Finished Motor*** | 4.4 (3%) | 6.7 (12%) | 2.7 (19%) |
| ***BOM Level 3 components in Unwound Armature*** | 3.9 (3%) | 4.5 (8%) | 1.4 (10%) |
| ***BOM Level 2 components in Magnet Body Assembly*** | 3.9 (3%) | 3.5 (6%) | 1.3 (9%) |
| ***Over levels 1, 2 and 3*** | 4 (3%) | 5 (9%) | 2 (13%) |

The degree of commonality index was measured for three sets of components: BOM level 1 components in the finished motor, BOM level 3 components in the unwound armature; and BOM level 2 components in the magnet body assembly. In addition it was calculated over these three BOM levels collectively. The commonality index measures are summarised in Table 5.7 and a detailed explanation of how they were calculated is presented in Appendix 17.

In general the final assembly components demonstrated the highest level of commonality, while the magnet body components demonstrated the least commonality. The components in the ETO motors were by far the least standardised, while those in the MTS motors provided the highest level of commonality. The components in the motors subject to FPp were found to have a lower commonality index than the MTS motors particularly the components in the magnet body assembly. The explanation for this lies in the fact that out of the 56 finished motor specifications, 23 involved invasive modifications to the magnet body assemblies, such as main pole winding changes, thermostat changes, and main pole bore changes (refer to Appendix 12 for details). The component commonality for the FPp motors could easily have been lower, however 16 of the stock modifications were limited to a change of data plate only, a component so trivial that it does not even fall within the scope of this analysis.

***Summary:*** only very few minor components were found to be common across each UoA - in fact no components were found to be common across the ETO motors. At each BOM level the ETO motors exhibited the lowest degree of commonality index – on average just one third of the commonality demonstrated by the FPp motors. The MTS motors exhibited the highest level of commonality. For each UoA the final assembly components (commonly the subject of postponed modifications) demonstrated the highest level of commonality, while the magnet body components demonstrated the least.

### *5.4.6 Excess Capacity*

No production record was made of downtime due to the lack of demand defined as excess capacity. Therefore, it was not possible to measure excess capacity directly. Instead the ratio of actual output to design capacity (capacity utilisation) was used as an indication of excess capacity – the lower it was the more likely excess capacity existed. Further, no data regarding design capacity or planned downtime was available for S&R where most of the UK stock modifications were carried out. Fortunately, however, 6 of the 38 UK stock motors modified from stock, and all of the 22 motors modified in production, were modified in the final assembly cell in the LDC area. Therefore, the final assembly cell - and the subsequent motor test and paint spray cells - were order-driven a greater proportion of the time than all the previous cells.

For the study period BC was not measuring capacity utilisation - simply all cells were envisaged to have a weekly capacity of 25 motors. Fortunately, the actual output for each cell (except for armature impregnation and finishing) was routinely measured, on a weekly basis. This data originated from the operator booking sheets, used to update the LDC Tracker and was available for 2002 only. Therefore the capacity utilisation measure was restricted to the six month period from January to June 2002 exclusively.

**Table 5.8: Capacity measures for selected LDC production cells (listed in order of production flow) for the six month period 1st January to 30th June 2002.**

| Cell | Labour levels | Weekly Design Capacity (motors) | Average Weekly Output (motors) | Capacity Utilisation | |
|---|---|---|---|---|---|
| | | | | Average Weekly | CV |
| ***Commutator build*** | 2 | 23 | 10 | ***43%*** | ***38%*** |
| ***Armature core*** | 1 | 22 | 9 | ***41%*** | ***37%*** |
| ***Armature assembly*** | 1 | 23 | 9 | ***39%*** | ***37%*** |
| ***Armature winding*** | 5 | 37 | 10 | ***26%*** | ***32%*** |
| ***Final assembly*** | 6 | 56 | 10 | ***18%*** | ***38%*** |
| ***Motor Test*** | 1 | 37 | 10 | ***26%*** | ***52%*** |
| ***Motor spray & pack*** | 1 | 56 | 9 | ***17%*** | ***55%*** |

Capacity utilisation was calculated for this study using the following formula:

$$\text{Weekly Cell Capacity Utilisation} = \frac{\text{Actual Cell Output (no. of motors)}}{\text{Cell Design capacity (no. of motors)}}$$

where

Actual Cell Output = weekly cell output

$$\text{Cell Design capacity} = \frac{\text{cell labour level x 37 hours}}{\text{cell process cycle time}}$$

Weekly capacity utilisation was calculated for each cell over the 26 week period and these measures are summarised in Table 5.8 (refer to Appendix 18 for more details). Cell design capacity was calculated using current labour levels, the BC standard 37 hour operating week, and estimated cycle times. The cycle times were estimated based on BC style operations, and had previously been verified with Bull Electric (Ipswich) operators. The average frame size produced over the six month period was ‘200’, therefore the cycle times associated with this size of industrial LDC motor were used.

It was apparent from the design capacities that those cells most often order-driven, final assembly, motor test and motor spray, were provided with greater capacity. The motor test cell only had the same design capacity as armature winding, but still far in excess of the envisaged capacity of 25 motors per week.

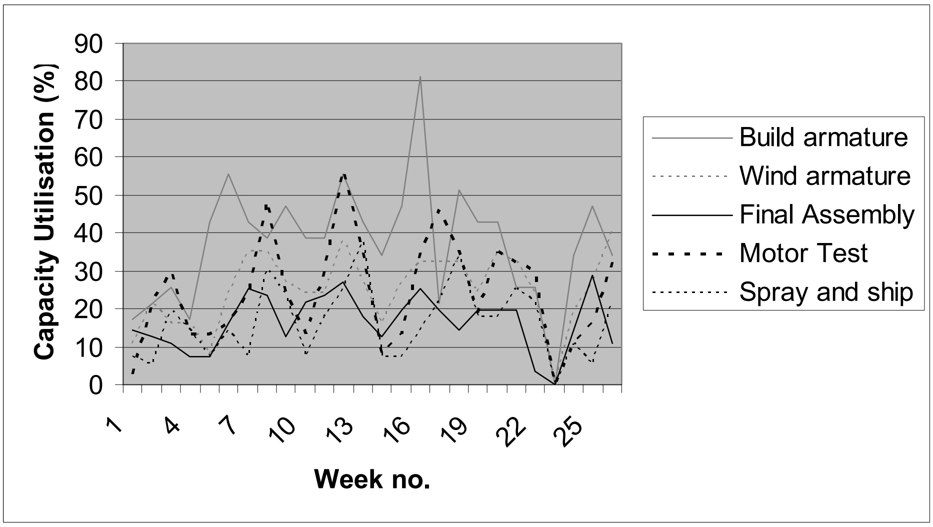



**Figure 5.4: The weekly capacity utilisation for selected cells for the six month period January to June 2002 exclusively**

The average weekly output for each cell was around 10 motors, less than half the envisaged available capacity of 25 motors and much less than the calculated design capacities. As a result the capacity utilisation levels were generally very low. The capacity utilisation levels at both the final assembly and motor spray cells were consistently the lowest (as illustrated in the graph in Figure 5.4) and averaged at 18%. This suggested that it was at these processes that excess capacity was likely to be greatest. The average utilisation of the motor test cell was the same as that of the armature winding cell but more variable. It should be considered that the motor test and spray cells are only required for a small proportion of stock modifications so the excess capacity at these cells was expected to be less than at the final assembly cell which is required for all modifications.

***Summary:*** in the absence of downtime records the capacity utilisation measure was used to indicate excess capacity. No capacity data was available for S&R, where the majority of the stock modifications were carried out. Instead capacity utilisation was measured for the LDC final assembly cell, where a third of stock modifications were performed. The design capacities of this cell and the subsequent motor test and spray cells indicated that these cells had been provided with the greater capacities than the preceding cells. Further, they consistently demonstrated the lowest utilisation levels over the 6 month period. This suggested that it was at these 'postponed' processes that excess capacity was likely to be the greatest.

### *5.4.7 Throughput Efficiency*

The value adding activities at BC were the *operations* identified on the flow process chart in Table 5.1. To calculate throughput efficiency the flow of material, with the longest lead-time, was followed through commutator manufacture, the armature assembly, motor assembly, motor test and motor spray. Therefore, the following processes performed in parallel were not measured: armature core manufacture, armature coil preparation, pole winding, and the magnet body assembly and impregnation.

The value added times for each motor were calculated from the estimated processing times based on BC style operations, and verified with Bull Electric, Ipswich operators (refer to Appendix 19). The processing times and the elapsed times were measured over the factory operating hours. Therefore the armature impregnation and motor painting processes (each estimated at 1.5 days) were equivalent to 11 hours operating time.

The total value added times for the smallest and largest motors differed by only 3 hours (8%). Given that the total elapsed time (which was the denominator in the throughput efficiency calculation) was measured in weeks rather than hours this differential was judged to be negligible. Therefore, the total value added time for the average sized motor demanded during the study period, frame size ‘200’, was used. The precise stock modification carried out on each FPp order was detailed on the Instruction sheets. The associated processing times were estimated by the Service Manager, who had 20 years experience with DC motors and was responsible for S&R (including stock modifications).

The elapsed time was measured from the motor works order release into the factory to the despatch, and booking into the warehouse, of the finished order. The works order release off the MPS and the booking into warehouse dates were sourced from the LDC Tracker sheet. The despatch dates were taken from the Order Log and cross-referenced with despatch notes. The elapsed time for the stock modifications was measured from the date the orders left mechanical engineering (as recorded on the Order Log) at which time they were available for manufacture.

A summary of the throughput efficiency measures is presented in Table 5.9. In common with the customer service measures it was necessary to split the FPp UoA into those motors modified in production, and those modified from stock. Unfortunately the required data was only available for 6 of the 22 motors modified in production therefore these results were excluded. Further it was not possible to link the production records for a particular UK stock motor to the customer order for it (modified from stock or ex-stock). Therefore the despatch date, and duration in the warehouse, was not known for UK stock motors. The throughput efficiency for UK stock motor works orders released between 1st May '01 and 31st April '02 was assessed. There was a high probability that these motors had been used for customer orders (stock modifications or ex-stock) due for delivery during the study period (1st July '01 to 30th June '02).

**Table 5.9: Throughput efficiency measures for the UoA.**

| ***Average Values*** | | ***Order Driven*** | | ***Stock Driven*** |
|---|---|---|---|---|
| | | ***ETO (Contract Motors)*** | ***FPp (Stock Modifications)*** | ***All UK stock motors MTS*** |
| ***No. of motors assessed*** | | 188 | 35 | 106 |
| ***Value added time*** | | 37 hrs | 6.4 hrs | 37 hrs |
| ***Time in warehouse*** | | 0.4 wks | 0.6 wks | No data |
| ***Elapsed time (excluding time in Warehouse)*** | | 6.3 wks | 1.9 wks | 10.8 wks |
| ***Throughput Efficiency (including time in warehouse)*** | | 16% | 14% | No data |
| ***Throughput Efficiency (excluding time in warehouse)*** | ***Average*** | 17% | 21% | 10% |
| | ***CV*** | 22% | 127% | 30% |
| | ***Range*** | 9 – 26% | 0.2 – 98% | 4 – 20% |

The elapsed time (or manufacturing lead-time) for the order-driven contract motors was much shorter than for the stock-driven UK motors - 6 compared with 10 weeks. The time in the finished goods warehouse was typically less than 1 week. However the UK stock motors were probably stored in the warehouse for much longer but, as explained, this data was unavailable. For the ETO motors the time in the finished goods warehouse had little impact on the throughput efficiency. However in the case of stock modifications the manufacturing lead-time was much shorter - 1.8 weeks. Therefore the

0.6 weeks in the warehouse had a greater impact on throughput efficiency and reduced it from 26% to 16%. Considering these issues, particularly the absence of despatch dates for UK stock motors, throughput efficiency measure excluded time in the finished goods warehouse.

The stock driven production of the UK stock motors achieved an average throughput efficiency of 10% compared with the 17% and 21% efficiencies achieved by the order-driven manufacture of the ETO motors and stock modifications respectively. As expected the stock modifications achieved higher throughput efficiency than the manufacture of the UK stock motors – almost double. However, the throughput efficiency achieved by the stock modifications was highly variable from order to order as the coefficient of variation (CV) of 127% shows. In fact on some orders where the modification was minor the throughput efficiency was as little as 0.2% lower than that achieved by any of the ETO or MTS orders. The main factor driving the variability in throughput efficiency was the variety of modifications which required anything from 10 minutes to 26 working hours.

The most striking difference between generic stock motor manufacture and the postponed modifications was not the throughput efficiencies but the manufacturing lead-times. Postponed modification was clearly more responsive with a manufacturing lead-time equivalent to only 18% of that for the generic stock motors.

***Summary:*** the stock driven production of the UK stock motors achieved a throughput efficiency of 10% compared with the 17% and 21% efficiencies achieved by the order-driven manufacture of the ETO motors and stock modifications respectively. As predicted the throughput efficiency achieved by the order driven modifications was higher than (double) that achieved by the manufacture of the UK stock motors. However the most striking difference was not the throughput efficiencies but manufacturing lead-times - 1.9 weeks for the modification compared to 10.8 weeks for the stock motors.

### *5.4.8 The Production Variety Funnel*

A PVF central to the conceptual model of FPp was drawn for each of the UoA. The PVFs for the ETO and the FPp UoA are shown in Figure 5.5 and Figure 5.6 respectively while the PVF for the MTS UoA is in Appendix 20.

The BOMs previously analysed for the product design measures (refer to section 5.4.5 for details) were used to plot the PVFs. The commutator parts were not available on the Cincom BOMs, therefore the variety in these parts was estimated using evidence from interviews with mechanical motor design engineers (refer to Appendix 20 for details).

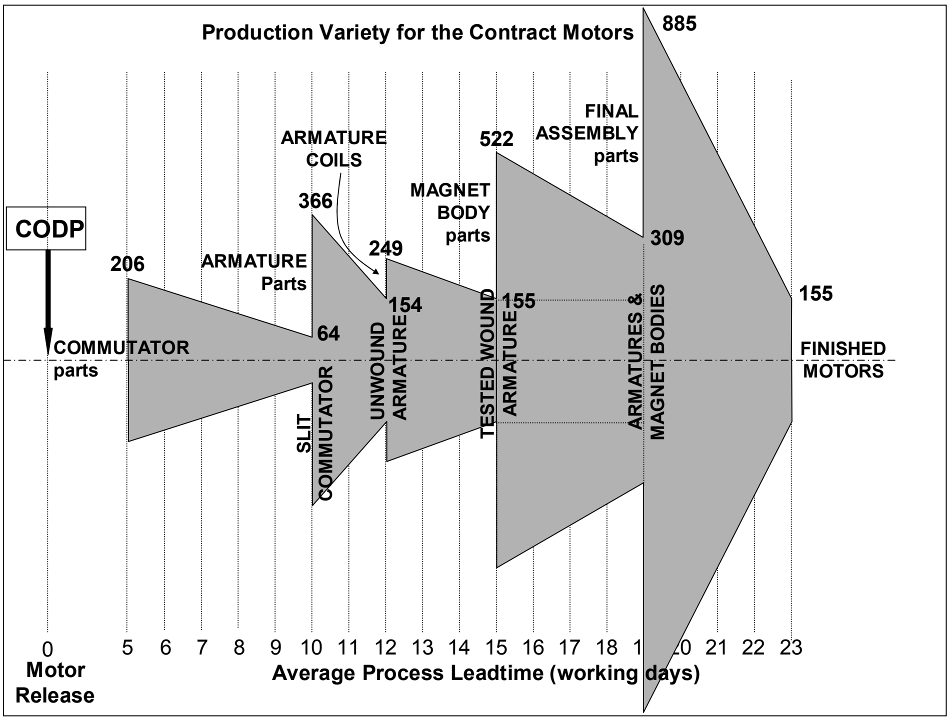



**Figure 5.5: The Production Variety Funnel for the ETO UoA (contract motors)**

The average process lead-times used for the PVFs were sourced from a lead-time analysis conducted by the LDC section in April '02 and are measured in working days. This evidence was corroborated by interviews with the LDC Planner and LDC Product Manager.

The PVF for the magnet body assembly is overlaid on that for the armature from the point where the armature completes testing - and triggers the magnet body assembly - to the point where it enters final assembly. Fortunately the armature production variety remains static over these manufacturing stages as no significant parts are added to it.

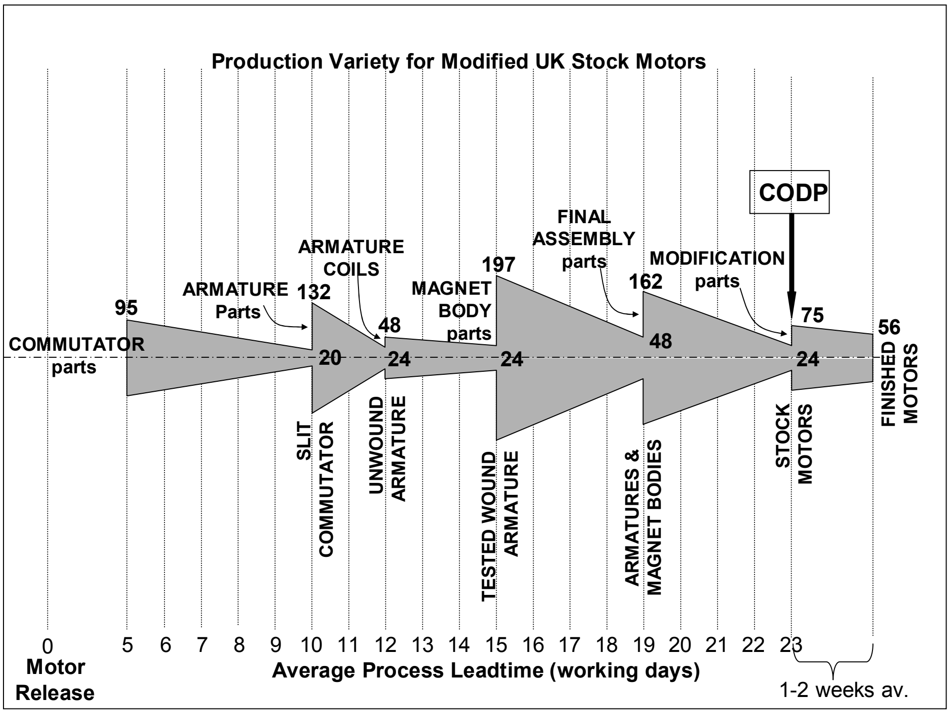



**Figure 5.6: The Production Variety Funnel for the FPp UoA (modified UK stock motors).**

The parts input at each major stage of production consisted of :

- assemblies that were manufactured on the LDC section (shown on vertical axis of PVF) such as the 'slit commutator',
- kits of parts from the machine shop and stores (shown on horizontal axis of PVF), such as the 'armature parts'. For full details of the 6 different part kits delivered to LDC manufacturing refer to Appendix 20.
- the armature coils which were made on the LDC section.

The PVF was basically the same complex shape for each of the UoA, exhibiting multiple 'necks' (narrow points) at the same stages in the manufacturing process. But the PVFs varied in their relative, and actual, widths at the various manufacturing stages. All of the PVFs exhibited their smallest 'neck' at the slit commutator stage, however this was only 10 working days into the manufacturing lead-time. Further all the PVFs, except that for the modified stock UoA, were widest at the input to the final assembly of the motor. For the ETO motors 885 distinct components were supplied to the final assembly, to make 155 finished motor variants.

The PVF for the motors subject to FPp covered the postponed modification process. The CODP was located at the standard UK stock motor which was the final 'neck' in the PVF and was of a similar size (in terms of the number of standard motors) to the smallest 'neck' at the slit commutator. In contrast the 'neck' in the ETO PVF at the generic motor specification stage (indicated by the number of tested wound armature specifications) was almost 2.5 times wider than the smallest neck at the slit commutator stage. Further it was equal to the number of finished motors, in other words even at the wound armature stage the motor were customised. This suggests that the modified motor approach was not suitable for the ETO motor range.

Considering the FPp application there are 24 generic motors at the CODP and a further 51 modifying components are supplied into the postponed assembly process. However many of these components are purchased against the customer order due to their high variety. Therefore the number of SKUs at the CODP is less than the 56 finished motor variants.

## 5.5 CASE ANALYSIS

In this section the results of the case analysis are presented: first the major flaws in this FPp application are discussed, and second the findings are compared with the hypotheses.

### *5.5.1 Removing Added Value*

All modifications involved the removal of parts (as well as adding new ones) which resulted in the removal of previously added value. Modifications commonly involved peripheral components such as tachometers mounted on the shaft, forced vent units or mounting brackets. The modifications required up to 4 hours. However almost half the motors modified (25 out of 60) also required far more invasive modifications involving changes to the magnet body components. This commonly involved a motor strip down which could take up to 3 working days depending upon the size of the motor.

Clearly the extent of added value removed was not insignificant and was far from ideal. The modifications were such that the variety in the magnet bodies in the finished motors (subject to FPp) was much greater than the number of UK standard motor variants (24) - probably closer to the finished motor variety of 56. The armature, however, was not subject to any modifications (following impregnation this was not possible) and its variety remained at 24 in the finished motors.

This suggested that the CODP would be better located further up stream in the manufacturing processes to avoid the removal of added value. A more suitable location for the CODP would be at the balanced armature stage, but before the magnet body was assembled. The manufacturing lead-time for the magnet body assembly and motor final assembly was just 8 working days. Therefore it would still be possible to provide modified standard motors on a 3 to 4 week lead-time.

This approach would have the added benefit of reducing the stock value from that of finished standard motors to balanced armatures. Alternatively the stock levels could be increased to improve ex-stock availability from 63% (percentage of orders for modified stock motors which were satisfied from stock). This would be advisable because the number of generic SKU would remain at the same level – the variety in the armatures is the same as the variety in the finished motors. Therefore the demand variability at generic level would remain high, so ex-stock availability would not be improved without higher stock levels.

The improved FPp application proposed above would naturally take the postponed motor customisation away from the S&R section (which had extremely limited resources and was primarily tasked with service and repairs) and relocate it back in the main LDC manufacturing section. Here the final assembly area, where motor customisation would take place, was shown to have substantial excess capacity.

### *5.5.2 Hypotheses Testing*

All hypotheses, except H3, were fully tested in the BC case study and the findings were largely as predicted by the six hypotheses. However one hypothesis was challenged in part (H5).

***What is the demand profile of products selected for manufacture under FPp?***

> **H1: Products are selected for manufacture under FPp rather than MTS when they exhibit high demand mix, high demand variability, and low volume demand at finished product level.**
>
> **H2: Products are selected for manufacture under FPp rather than MTO/ETO when they exhibit high volume demand at generic product level.**

The findings fully supported both hypotheses H1 and H2. The motors manufactured under FPp were demanded in four times as many variants as the MTS motors, 56 compared to 14 variants. As a result the average demand variability at finished motor level was higher for the FPp motors at 341% compared to 292% for those motors MTS. The average volume demand for finished motors was lower for the motors manufactured by the FPp approach than by MTS, 1.1 compared to 1.6 motors. The demand analysis showed that overall the industrial LDC motors were required in extremely high variety and relatively low volumes, resulting in very high demand variability. A total of 347 LDC motors were ordered in 238 variants over the one-year study period, an average of 1.5 motors per variant. Two-thirds of these motors were manufactured as ETO motors.

As expected the average volume demand at generic level for the FPp motors was higher than that demonstrated by the ETO motors 2.6 compared to 1.5 motors. This was because the generic level FPp motors were recognised standard UK specification motors demanded by multiple customers, whereas the generic level ETO motors were non-standard motors demanded by one customer. This indicated that the 30 UK stock motor specifications were selected for the FPp application by specification and possibly demand volume. However, it was not possible to confirm this, because Bull Electric made the selection prior to the relocation of LDC manufacture to BC.

***What is the impact on customer service of FPp?***

> **H3: FPp considered as an alternative to MTS increases ex-stock availability.**
>
> **H4: FPp considered as an alternative to MTO/ETO reduces order lead-times and increases delivery reliability but introduces demand amplification**

Hypothesis H3 remains untested. This hypothesis pre-supposes that orders subject to FPp and MTS do *not* pull from the same product stocks, however in the BC study this was the case. Further, it was only possible to measure ex-stock availability in terms of the proportion of orders (rather than orders *and enquiries*) for which the correct stock motor was available. Consequently this measure ignored the many enquiries which did not translate into orders because the stock motor was not available. However, even using this extremely lenient measure of ex-stock availability only 63% of FPp orders could be satisfied from stock (while the remainder were modified in production). This was because the UK motor stock levels were maintained at only 50% to 70% of target due to their high value and unpredictable, erratic demand.

The study findings fully endorsed hypothesis H4. Demand amplification was measured for all UoA and as expected was *not* detected for the ETO UoA. A degree of demand amplification was found for the manufacture of the generic stock motors, particularly at the balanced armature and the shipped to warehouse schedules. As expected no demand amplification was detected for the order-driven stock modifications. These findings support hypothesis H4 showing that applying FPp introduced a degree of demand amplification which did not exist for the ETO approach.

The average order lead-time achieved by orders using the FPp approach was 3 weeks, less than a quarter of that achieved by ETO orders. As expected this was in part because much of the UK standard motor was manufactured speculatively to stock rather than to order. This reduced the manufacturing lead-time from 7.3 to 2.5 weeks. However dramatic reductions in both engineering and bought-in parts lead-times also contributed to the reduction in order lead-time.

As predicted by hypothesis H4 the delivery reliability demonstrated by FPp orders was higher than for ETO orders, 70% compared to 63% respectively. However, the improvement in delivery reliability provided by FPp was unexpectedly modest.

There are three possible explanations:

- quoted lead-times for the modified motors (FPp) did not take into account the availability of parts required for modifications and few of these parts were stocked. In addition the process of acquiring parts was very laborious, since modifications were managed outside the MRP system,

- the extremely limited nature of resources in S&R (where the majority of motor modifications took place), coupled with the fact that S&R were primarily tasked with service and repairs, may have led to the unresponsive execution of modifications.

- low standard motor stocks, providing only 63% availability for modified motor orders, may have extended the manufacturing lead-time and reduced delivery reliability.

***What are the product design implications of applying FPp?***

**H5: Product families subject to FPp will have a higher level of standardisation and modularity than product families subject to MTO/ETO**

Hypothesis H5 was only partially supported by the findings. As predicted by the motors subject to FPp exhibited greater product standardisation than those ETO both in terms of common components and the degree of commonality index. Only minor components were found to be common across each UoA and in fact no components were common across the ETO UoA. Overall the commonality index for the FPp UoA was three times that for the ETO UoA and it was higher at every level in the BOM. At the lower BOM levels this was due to the use of standard UK motors for FPp however at the level where modifications normally took place it was simply due to the customers' requirement for less variety.

Contrary to hypothesis H5, all motors, regardless of inventory management policy, exhibited the same level of modularity. The major sub-assemblies in the LDC motors exhibited a very low degree of modularity as dictated by the basic design of the motor. However groups of peripheral components and sub-assemblies - generally involved in final assembly - did correspond to particular functions on a one-to-one basis, thereby exhibiting a high degree of modularity. The majority of the stock modifications involved only highly modular components, many of which were peripheral. However about a quarter involved components which demonstrated a relatively low degree of modularity and were embedded within a major sub-assembly.

***What are the manufacturing planning and scheduling implications of applying FPp?***

**H6: Capability of the postponed transformation process to respond to high demand variability requires excess capacity and high throughput efficiency**

The findings supported hypothesis H6. In the absence of planned downtime records the capacity utilisation measure was used to indicate excess capacity. No capacity data was available for S&R where the majority of the stock modifications were carried out. Instead the capacity utilisation measure was applied to the LDC final assembly cell, where a third of stock modifications were performed. The design capacities of this cell - and the subsequent motor test and spray cells - indicated that these cells had been provided with greater capacities than preceding cells. Further they consistently demonstrated the lowest utilisation levels over the 6 month period measured. This suggested that it was at these 'postponed' processes that excess capacity was likely to be the greatest.

As predicted by hypothesis H6 the throughput efficiency for the postponed modifications (conducted in S&R from stock) was higher than (double) that achieved by the stock-driven manufacture of the generic stock motors. The modifications achieved 21% throughput efficiency compared to 10% achieved by the manufacture of the generic motors. However, the throughput efficiency achieved by the postponed modifications was highly variable from order to order (four times more variable than for manufacture of the generic stock motors) as the coefficient of variation of 127% demonstrates. The main factor driving the variability in throughput efficiency was the variety of modifications, which required anything from 10 minutes to 26 working hours. The most striking difference between generic stock motor manufacture and the postponed modifications was not the throughput efficiencies but the manufacturing lead-times. Postponed modification was clearly more responsive with a manufacturing lead-time equivalent to only 18% of that for the generic stock motors.

***Production Variety Funnel:*** The number of SKUs at the CODP was less than the number of finished motors demanded. However, this was only the case because many of the components supplied into the postponed process were purchased against the customer order due to their high variety. This supported the original conceptual model of FPp which predicted the number of SKUs at the CODP to be less than the number of finished items.

## 5.6 CONCLUSIONS

At BC the FPp application was sustainable and provided the level of responsiveness required by customers. However it was not an ideal application. Despite this the hypotheses remained largely unchallenged. The customising process involved the removal of previously added components, which suggested that the CODP would be better located further up stream in the manufacturing process. A more suitable location for the CODP is proposed which would still enable the required order lead-time to be met. This approach would have the added benefit of allowing generic stock levels to be increased to improve ex-stock availability without increasing stock value. Further the postponed process would naturally be re-located to the main production area where substantial excess capacity exists.

Despite the flaws in the FPp application at BC no hypotheses were challenged as a result of anomalies in the findings. However the product modularity findings fundamentally challenged the hypothesis. Contrary to predictions product modularity was not related to the inventory management policy. All the motors demonstrated the same levels of modularity.

# CHAPTER SIX

## 6 Study at Dewhurst

The FPp application at Dewhurst most closely resembled an ideal application despite the fact that the implementation was not as planned. The Encrypted Pin Pad keypad was the only product studied which had been specifically designed for manufacture using the FPp approach. However the planned FPp application never came to fruition because the demand profile for the keypad variants was not as forecasted by the customer. Consequently many more component stocks were required and the postponed processes were more extensive than planned.

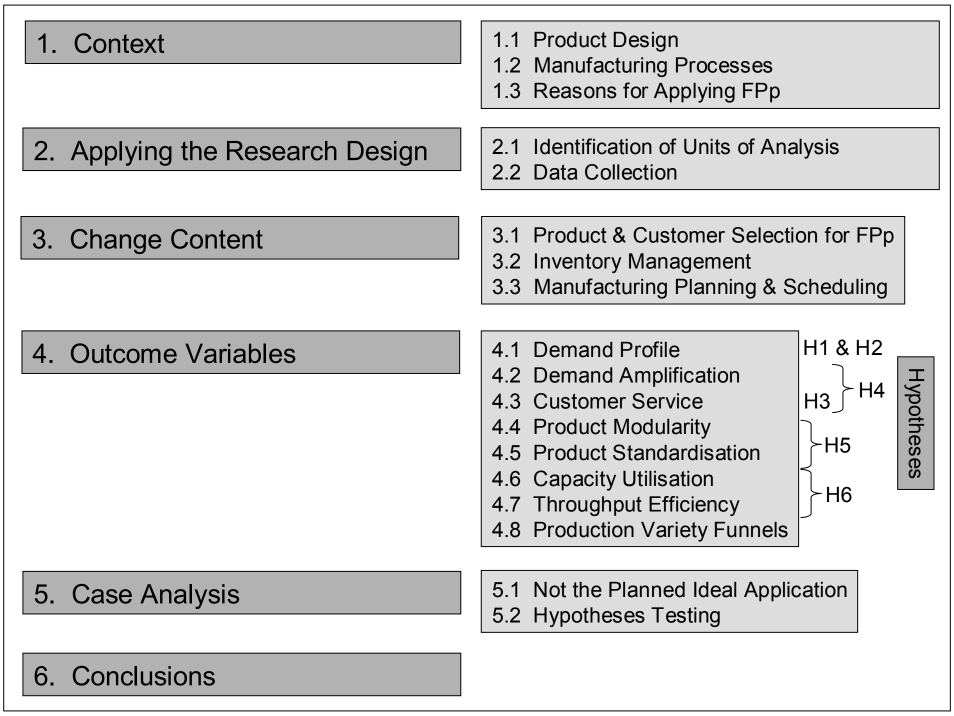



**Figure 6.1: Diagram illustrating the structure of the case study chapters**

In common with the other case study chapters this is structured according to the diagram in Figure 6.1. The contextual features relating to FPp are presented in the first part which includes descriptions of the products subject to FPp, the manufacturing processes used to make them and the reasons for applying FPp. The key aspects of how the research design was applied in this specific study are described in the second part.

The ‘change content’ when FPp was applied in a previously MTO and MTS environment is described in the third section. This includes selection of products and customers for FPp, changes to inventory management and manufacturing planning. In the fourth section the ‘outcome variables’, which are the quantitative concepts tested in the hypotheses, are presented. The case analysis is presented in the fifth section which includes an evaluation of the major flaws in the FPp application and testing of the hypotheses against the findings. The chapter closes with conclusions from the study.

## 6.1 CONTEXT

Dewhurst plc was a leading independent supplier of control systems and related components. Their products included keypads for ATMs (Automated Teller Machines), lift components and rail components. This case study was performed at the main Dewhurst manufacturing facility located in Hounslow, UK. This factory employed around 160 people, 80 of whom were direct manufacturing labour. Its annual turnover was about £13 million and almost three-quarters of this was accounted for by one customer, NCR. NCR manufactured and supplied the complete dispensing machine to banks all over the world and Dewhurst had been NCR’s sole supplier of ATM keypads for about 10 years.

In 2001 Dewhurst developed a high specification, standardised, yet highly configurable keypad, EPP (Encrypted Pin Pad) to replace the entire range of keypads previously supplied to NCR. The EPP keypad was specifically designed to be manufactured using FPp - termed ‘last minute configuration’ by Dewhurst - and therefore was an ideal subject for this case study.

Dewhurst planned that by summer 2003 the supply of the old style keypads to NCR would be terminated and that the EPP keypad would be supplied to all NCR regional divisions - not just the UK division as was the case during the study. In the long term it was envisaged that the EPP keypads would be supplied to the NCR regional divisions via the Dewhurst subsidiaries (in North America, Canada and Australia) who would configure the keypads.

### *6.1.1 Product Design*

The EPP keypad, shown in Figure 6.2 consisted of a die cast body within which was assembled die cast keytip holders (termed keyskirts), a shim, a rubber mat, a PCB, and a resistor assembly. The keypad was enclosed by a screw-down backplate. This stage in the manufacturing was known as an 'unconfigured keypad' because the keypad had not yet been populated by the configuration of keytips required by the specific bank. The keytips, ten numeric and up to six function keys, were glued into the keyskirts. Crucially the keytips were demanded in high variety which was generated by variations in the keytip material, legend, and embossing.


**Figure 6.2: Picture of the steel keytip variant of the EPP keyad.**

Two other products were also studied to enable the comparison between FPp and MTO and MTS. The MA keypad appeared very similar to the EPP keypad, as illustrated in Figure 6.2, however there were two crucial differences. Firstly, the MA keypad was available in 3 different layouts: the MA11 had sixteen keys like the EPP keypad; the MA10 had twelve keys; and the MA12 had four keys. Further a special range of MA keypads had been developed for the biggest customer Fujitsu. The implications for the MA keypad range were that the keypad body was required in six different designs, whereas the EPP keypad body was only required in one generic design. The second crucial difference was in the way the keytips were secured, the MA keytips were secured by metal studs welded to the back, whereas the EPP keytips were secured by glue. This meant that the MA keytips had to be assembled *first*, whereas the opportunity was available to assemble the EPP keytips last, and postpone the configuration of the keypad until a customer order had been received.

The third product studied was the lift pushbutton (PB) body. This was quite a different product to either of the keypads, however it too required a manual assembly process. The PB body consisted of a body moulding within which was assembled a pair of contacts with moulded covers, illumination terminals and main power terminals. The contacts were made up of an intricate assembly of mechanical components such as springs, flexing arms and moulded plungers. The variety in the PB body was driven by a number of options: the body type (switch or just indicator), whether it was to be illuminated or not; the configuration of the pair of contacts (normally open or normally closed); and the type of power terminals.

### *6.1.2 Manufacturing Processes*

The flow process chart in Table 6.1 shows a summary of the manufacturing processes required to make each of the products studied. For the full breakdown of keypad operations refer to Appendix 21.

A number of general observations can be made about the manufacturing processes:

- the three product groups were manufactured at different work centres,
- manufacturing processes consisted of assembly operations except for the PB body plastic components which were injection moulded,
- assembly processes were manual, and machines only employed for the gluing of the EPP keytips and the laser marking of the plastic EPP keytips.

The production arrangement for each of the three products was different. The MA keypads were fully assembled at individual work stations whereas the PB bodies were assembled by a production line albeit consisting of only two people. The production arrangement for the EPP keypads was more complex as detailed in Appendix 22.

**Table 6.1: Flow process charts with operations summarised**

| Process Description | Symbols | | | |
|---|---|---|---|---|
| **MA Keypads** | | | | |
| Kit of material issued by stores | ○ | □ | ➡ | ▽ |
| **Keypad assembled on w/c 700** | ● | □ | ⇨ | ▽ |
| Keypads mechanically & visually inspected at **w/c 906** | ○ | ■ | ⇨ | ▽ |
| **Keypads packed into individual cartons on w/c 700** | ● | □ | ⇨ | ▽ |
| Keypads book into & out of stores & sent to despatch | ○ | □ | ➡ | ▽ |
| **EPP Keypads** | | | | |
| Kit of material issued by stores | ○ | □ | ➡ | ▽ |
| **Unconfigured keypad assembled on w/c 702** | ● | □ | ⇨ | ▽ |
| Keypads electrically and mechanically tested | ○ | ■ | ⇨ | ▽ |
| **UNCONFIGURED KEYPAD STORED** on shopfloor | ○ | □ | ⇨ | ▼ |
| Unconfigured EPP keypads moved to assembly area | ○ | □ | ➡ | ▽ |
| **Keytips glued and located in keyskirts on w/c 711** | ● | □ | ⇨ | ▽ |
| **Plastic keytips laser marked on w/c 712** | ● | □ | ⇨ | ▽ |
| Keypads visually inspected & packed in boxes of 12 | ○ | ■ | ⇨ | ▽ |
| Keypads moved to despatch | ○ | □ | ➡ | ▽ |
| **PB Bodies** | | | | |
| **Plastic components injection moulded on w/c 202/5** | ● | □ | ⇨ | ▽ |
| **Plastic components finished on w/c 208** | ● | □ | ⇨ | ▽ |
| Plastic components moved to stores | ○ | □ | ➡ | ▽ |
| Plastic components stored as stock item | ○ | □ | ⇨ | ▼ |
| Kit of material issued by stores | ○ | □ | ➡ | ▽ |
| **PB bodies assembled on w/c 703** | ● | □ | ⇨ | ▽ |
| PB bodies electrically tested & packed in boxes of 250 | ○ | ■ | ⇨ | ▽ |
| PB bodies moved to stores | ○ | □ | ➡ | ▽ |
| PB bodies stored as stock item | ○ | □ | ⇨ | ▼ |
| **Operation** | ● | | | |
| **Inspection** | | ■ | | |
| **Transport** | | | ➡ | |
| **Storage** | | | | ▼ |

The assembly of the unconfigured EPP keypads was always conducted on production lines of three people. The gluing and populating (termed configuration) of the keypads was initially conducted at individual work stations. However about 1.5 months into the study period a gluing machine was commissioned which meant that the gluing and populating operations had to be divided. Accordingly a configuration production line of three people was established. Both the assembly and configuration lines employed single piece flow and the operations were balanced to synchronise work flow.

### *6.1.3 Reasons for Applying Form Postponement*

The reasons for applying FPp (and how it was applied) was the subject of interviews with six different informants. The informants were selected because of their close involvement with the development of the EPP keypad and the establishment of its manufacture. The informants were the Keypads Account Director, Works Manager, Planning Manager, Process Engineering Manager, Design Project Leader and Materials Manager. Each informant was asked:

> ***Why was form postponement applied - what were the drivers?***

The Keypads Account Director maintained that it was Dewhurst who (from as early as 1998) persuaded NCR that if one keypad design could be created, to replace the existing proliferation of designs, this would have significant benefits for both companies:

> *'Dewhurst sold the idea of 'one size fits all' to NCR over a period of time which saw increased demands on the keypad technology and the need for reduced lead-times'*

Managing the different keypad models for NCR created significant problems for Dewhurst as the Keypads Account Director explained:

> *'The seven different keypad models were required in potentially hundreds of variants on a short lead-time. Not only did this drive component inventories to a very high level, but it proved complex to manage.'*

The keypads were MTO, but to reliably meet the lead-times demanded by NCR, it was necessary to maintain stocks of *all* the keypad components. The problem of high component inventory was compounded by NCR's requirement of increased responsiveness. This formed part of NCR's effort to offer reduced lead-times to their ATM customers - the banks. In 1998 Dewhurst were supplying the keypads on a 10 day lead-time. However this was halved to 5 days by the middle of 2001.

Dewhurst argued that a ‘one-size fits all’ approach would allow the number of different components (and their associated inventories) to be radically reduced. More importantly to NCR it would enable ‘last minute configuration’ and potentially an even more responsive supply.

From NCR’s point of view there were a number of converging factors that persuaded them that the standardised EPP keypad was of benefit. Firstly, they required a more responsive supply of keypads as discussed. Secondly, there was pressure in the ATM market for significant improvements in keypad technology, which meant that NCR would be forced to redesign their range of keypads. The required technology improvements included a change in cryptographic requirements driven by Visa, where the cryptographic module processes the PIN number. Further more stringent security standards had been set by ZKA a German organisation that regulates security on keypads.

***Summary:*** the key drivers for applying FPp to the manufacture of the EPP keypad were to improve responsiveness while reducing the high component inventory levels associated with the MTO of multiple keypad designs. Responsiveness was improved from the minimum standard lead-time of 5 working days to an average order lead-time of 3 working days. This was, in spite of the fact, that the FPp application was not as originally intended and required more customer order driven processes as later described in section 6.5.1.

## 6.2 APPLYING THE RESEARCH DESIGN

The identification of the units of analysis and the various issues concerned with data collection at Dewhurst are addressed in this section.

### *6.2.1 Identification of Units of Analysis*

Similarly to the previous studies each unit of analysis (UoA) was based around a *product group* subject to a particular *inventory management policy* (FPp, MTO or MTS). In contrast to the previous two case studies, an entire product group was manufactured using FPp at Dewhurst, therefore it was necessary to select *three different product groups* for the UoAs.

All EPP keypads manufactured by Dewhurst for NCR were subject to FPp. Dewhurst manufactured unconfigured keypads (and associated keytips) speculatively to stock, and subsequently populated the keypads with keytips to specific customer orders. As discussed in the context section the keypads supplied to NCR accounted for three-quarters of Dewhurst's turnover and were scheduled to replace the existing range of NCR keypads. Understandably this made the EPP keypad a very significant and important product for Dewhurst, and an ideal product group for the FPp UoA.

Ideally the product groups selected for the three UoAs should be as similar as possible in terms of general design and manufacturing processes. This ensures that the comparison between the different inventory management policies (FPp, MTO and MTS) screens out product specific factors. Therefore the MA keypad range was chosen for the MTO UoA. This range had a very similar design to the EPP keypad, but differed in that it was developed and manufactured by Dewhurst for sale to a variety of customers. The MA keypad was highly configurable and also used in ATMs, as well as other applications such as access systems.

Unfortunately no keypads were made-to-stock (MTS). The closest product, in terms of manufacturing processes (which was produced in sufficient volumes) was the body component for the 'Compact 2' range of lift pushbuttons (PB). The PB body component was MTS by Dewhurst in a number of variants and was chosen for the MTS UoA.

The keytips for both MA and EPP keypads, although of a slightly different design, were manufactured to Kanban stocks using the same manufacturing processes. It was decided therefore, that keytip manufacture should be ruled outside the scope of the study and keytips treated as an outside component supply to the manufacture of the two keypads.

Each PB body incorporated around four different plastic components injection moulded to stock by Dewhurst. The manufacture of these components was included in the study because their manufacture was part of the stock-driven processing of the PB bodies.

Each UoA was based around one of the three product groups selected and included the respective customer orders due for delivery within a *certain time period*. Considering the appropriate time period, the EPP keypad was developed in 2001 and first supplied to NCR in May 2002. However the keypad specification continued to be subject to minor changes by NCR until the beginning of September 2002 - this disrupted the supply of materials. Further, the stocks of unconfigured keypads were not established until the end of September 2002. Therefore, it was appropriate that the study period should begin on 1st October 2002, when the FPp approach to the manufacture of the EPP keypads was established and stable. Given the high volumes of orders for the EPP keypad it was determined that four months would be a sufficient time period for the study.

**Table 6.2: Unit of analysis orders due for despatch between 01/10/02 and 31/01/03**

| *Product Group* | *Orders* | *Volume* |
|---|---|---|
| *EPP (FPp)* | 598<br>(56% steel) | 26890 units<br>(24% steel) |
| *MA Keypads (MTO)* | 45 | 1154 units |
| *PB bodies (MTS)* | 89 | 44035 units |

Table 6.2 shows the orders and volume of products due between 1st October 2002 and 31st January 2003. The lowest number of orders due was for the MA keypads, however it was judged that 45 orders provided sufficient data for the customer service measures.

### *6.2.2 Data Collection*

In order to study a sufficient number of customer orders it was necessary to study a four-month period as argued during the identification of the UoA. In view of the ready availability of historic data it was decided to conduct a retrospective study. The majority of the data was collected for the four-month period between 1st October '02 and 31st January '03.

A retrospective study can raise questions regarding the *reliability* of the data. Interview data naturally required support from documentary and/or database evidence, and fortunately all the interviewees were not only still employed at the factory, but in the same roles, as for the study period. This meant that all the informants had first hand experience and knowledge of the time period in question.

A particularly productive source of evidence for demand profile, customer service and product design *measures* was the fully integrated MRPII system, MAPICS. Several modules had been implemented, including the main inventory management module around which various other modules operated: the bill of material module; the material purchasing module; the customer order module; the manufacturing order module; and the capacity planning module. Within the manufacturing order module the shop tools module interfaced with PMCS (described in section 6.3.3) and updated MAPICS minute by minute with job progress data.

With regards to reliability the data retrieved from MAPICS was no less reliable or accessible during the study than when it was generated. However, the retrospective nature of the study meant that data was not available to measure ex-stock availability in terms of the proportion of *enquiries* for which the correct product was available. However, a stock level history was available providing an indication of this measure for both the EPP keypads subject to FPp and the PB bodies sold direct ex-stock.

Overall the reliability and completeness of the data were only marginally affected by the retrospective nature of the study.

## 6.3 CHANGE CONTENT

In this section the changes required to apply FPp in a MTS and MTO environment are described including: product and customer selection, inventory management and manufacturing planning and scheduling changes.

### *6.3.1 Product and Customer Selection for Form Postponement*

In common with 'the reasons for applying FPp', how products and customers were selected for FPp was the subject of interviews with six different informants (previously listed in section 6.1.3). The two questions asked of all informants, and their collective answers, are presented below:

***Was the 'last minute configuration' (FPp) approach limited to certain customers, and if so why?***

Yes, FPp was limited to NCR because the EPP keypad - manufactured using the FPp approach - was exclusively designed and produced for NCR.

***Was the 'last minute configuration' (FPp) approach limited to certain product specifications, and if so why?***

Yes, FPp was limited to the EPP keypad and was not applied to Dewhurst's MA keypad range because the MA keypad design did not permit 'last minute configuration'. Both MA and EPP keypad variety was generated by keytip configurations and the keypad body was relatively standardised.

The crucial difference between the EPP and the MA keypads was in their construction. The MA keytips were secured in position by metal studs welded to the back of the keytips, rather than glue or clips used for the EPP keytips. This necessitated that the MA keytips be assembled *first,* ruling out the possibility of 'last minute configuration' because configuring the keytips was the first operation. Conversely the EPP keytips could be glued or clipped into the keyskirts during the final operation after the keypad body had been assembled.

Although all EPP keypads were selected for FPp, it could only be applied to a *predefined* list of finished keypad part numbers. This was because the manufacture of the keytips required numerous distinct processes therefore a long lead-time (steel keytips) or a high batch quantity. Therefore only keypads using the keytips stocked in Kanbans could be offered on a short lead-time.

### *6.3.2 Inventory management*

Inventory management encompassed order processing and the subsequent control of stocks, including keypad keytips, unconfigured EPP keypads and finished PB bodies. Also considered in this section - and inherent in the inventory management approach - is the Customer Order Decoupling Point (CODP) location.

Evidence for inventory management was gathered from interviews with the NCR Business Administrator, NCR Product Manager, Keypad Demand Manager, Lift Sales Co-ordinator and Planning Manager. It was supported by evidence from the MRPII system MAPICS. A flow chart illustrating the order processing and stock control procedure can be found together with a detailed description in Appendix 21. The key features of the inventory management approach are summarised in Table 6.3.

**Table 6.3: The main features of the inventory management policies compared for the UoA.**

| ***Features*** | ***MTO (MA Keypads)*** | ***FPp (EPP Keypads)*** | ***MTS (PB Bodies)*** |
|---|---|---|---|
| ***Demand information received from customer*** | Purchase orders | Purchase orders via EDI<br>Rolling forecasts (12 months & 12 weeks)<br>Delivery JIT schedule covering next 2 weeks | Purchase orders |
| ***Standard quoted lead-time*** | 3 weeks | 1 week<br>(allowed to deliver up to 3 working days early) | 1 week |
| ***Components for order-driven process*** | Components and keytips | 3 unconfigured keypads and keytips | n/a |
| ***Component supply*** | Components… MRP stock replenishment | Unconfigured EPP keypads and PB bodies …. MRP stock replenishment | |
| | Keytips… Kanbans | | N/a |
| ***CODP location*** | Body components and keytips | Unconfigured keypads | PB body stocks |

EPP keypad orders were rapidly processed by the Order Processing Department (OPD). They were received from NCR every morning via EDI (Electronic Data Interchange) at 9:00am. OPD then aimed to log the orders in the MAPICS Sales Order Book by 9:30am and release them into manufacturing. It had been agreed with NCR that Dewhurst would deliver all orders on time and in full when the lead-time given was 5 days or more. The implications for Dewhurst were that production capacity, particularly at the order-driven EPP configuring process, must be very flexible and easily ramped up (further discussed in section 6.4.6).

High stocks of the unconfigured keypads were always kept by Dewhurst and normally NCR ordered EPP keypads from an established list of finished part numbers. This enabled Dewhurst to ensure that all keytips on these keypads were continually available under a Kanban system. It was not possible to MTO the keytips due to their long manufacturing lead-time. The manufacture of the steel keytips involved numerous distinct processes conducted in up to nine different work centres, and the stamping and etching processes required a minimum batch quantity of 300.

The stocks of unconfigured keypad and finished PB bodies were ultimately controlled by the Planning Department who released the MAPICS recommended stock replenishment orders and were empowered to change the suggested quantities. The safety stock levels for the unconfigured EPP keypads were set at 2 weeks forward cover on the basis of NCR's anticipated demand of 3000 keypads per week. However this level of demand did not materialise. Over the 4 month study period (1st October '02 to 31st January '03) the average weekly demand was 1680 keypads. The charts in Appendix 21 show that the stock levels were around 3000 unconfigured keypads for the first 2 months of the study and then rapidly increased to around 6000 keypads. Unfortunately the demand did not increase therefore stock levels rose from about 2 weeks to almost 4 weeks cover.

The PB bodies were subjected to both dependant demand (as in the case of the unconfigured EPP keypads) and independent demand from numerous customers. The study was confined to the latter independent demand where the PB bodies were sold direct to customers and not incorporated into the fully assembled PBs. The PB body set safety stock levels varied, depending on the historical demand, ranging between zero for two variants up to 2000 for the standard variant. However, quite often the actual stock levels were five times, or more, their target level as the charts in Appendix 21 show.

### *6.3.3 Manufacturing Planning and Scheduling*

Manufacturing planning and scheduling covers the process from the manufacturing orders being released to the factory orders being scheduled and monitored through the operations.

Evidence for manufacturing planning and scheduling was gathered from interviews with the NCR Business Administrator, NCR Product Manager, Keypad Demand Manager, Lift Sales Co-ordinator and Planning Manager. It was supported by evidence from the MAPICS MRPII system.

A flow chart illustrating the manufacturing planning and scheduling process, together with a detailed description, can be found in Appendix 21 and a summary of the main features is presented in Table 6.4. Manufacturing orders for order driven production of the finished MA and EPP keypads were raised by OPD and automatically released. Prior to this - in the case of MA keypads - OPD checked material and capacity availability to ensure the lead-time could be met. However both material and production capacity were *assumed* to be available for the configuration of the EPP keypads.

**Table 6.4: Main features of manufacturing planning compared for stock replenishment orders, MTO and FPp.**

| ***Features*** | ***Stock Replenishment Orders*** | ***MTO (MA Keypads)*** | ***FPp (EPP Keypads)*** |
|---|---|---|---|
| ***Manufacturing orders*** | Processed by MRP system driven by one week period MPS | Processed by MRP system | By-passed MRP system |
| ***Customer orders entered onto SOB*** | n/a | Any time | Daily 9:00am |
| ***Release manufacturing orders to shopfloor*** | Weekly by Planning Manager | 3 times daily automatically | Daily at 10:30am manually |
| ***Order processing and manufacturing planning lead-time*** | 1 week | 11 working hours (average measured) | 1.5 working hours |

No stock replenishment manufacturing orders (including those for generic EPP keypads) were *automatically* released instead the MRP system made recommendations and the Planning Manager released orders into the factory. Available capacity was determined by a Work Centre Load Analysis generated by MAPICS. However the Planning Manager only intervened when there was a significant change in a work centre overload. Effectively production planning assumed the availability of infinite capacity.

Released manufacturing orders were downloaded three times daily from MAPICS to PMCS (Production Monitoring and Control System) with the exception of finished EPP keypad orders which are discussed later in this section. For MA keypad orders this ensured an average delay of 4 hours, and a worst case delay of 8 hours, between the manufacturing order being created by OPD and being available on PMCS for manufacturing. PMCS was a shop-floor computerised system which monitored job progress using an operation booking system. It provided each work centre with a 'load sheet' listing jobs in due date order. The Operators were able to view the load sheet and normally processed the jobs in the sequence recommended.

Finished EPP keypad manufacturing orders, once created by OPD, by-passed the MRP system and PMCS to ensure a rapid response from production. Hard copies of the EPP keypad manufacturing orders were passed to the Keypad Demand Manager checked and delivered to Production typically by 10.30am - only 1.5 hours after the customer orders were sent via EDI to Dewhurst. Once in production the EPP orders were immediately kitted and then processed in due date order according to the Sales Order Book.

***Summary:*** in general the manufacturing planning and scheduling system at Dewhurst was very responsive. The MRP system was run on a nightly basis and released manufacturing orders were downloaded 3 times each day to PMCS which automatically scheduled jobs in due date order. Nevertheless the finished EPP keypad manufacturing orders were given special treatment and by-passed the MRP system and PMCS to ensure a rapid response from production.

## 6.4 OUTCOME VARIABLES

The measures taken will be presented and compared for the three UoAs over the following eight sub-sections. The first section presents the demand profile measures, demand volume, mix and variability. In the second section the demand amplification plots are discussed. The customer service measures including ex-stock availability, order lead-time and delivery reliability are analysed in the third section. The fourth and fifth sections address product modularity and standardisation. Capacity utilisation measures and throughput efficiency measures are presented in the next two sections and finally the production variety funnels are compared.

### 6.4.1 Demand Profile

Evidence for the three demand measures was gathered from the MAPICS customer order module, onto which all customer orders were logged upon receipt. Where order numbers covered multiple items each order for a quantity of a particular item due on a particular date was treated as a separate order.

The demand measures are summarised in Table 6.5. For the full statement of demand for each end item in the three UoA refer to the tables in Appendix 23. The CV of demand was calculated from the weekly demands for each generic and end item over the four-month study period.

**Table 6.5: The demand measures compared for the UoA**

| *Measures* | *MTO (MA Keypads)* | *FPp (EPP Keypads)* | *MTS (PB Bodies)* |
|---|---|---|---|
| *No. of orders* | 45 orders | 598 orders | 89 orders |
| *Av. no. of orders at end item level* | 1.5 orders | 8 orders | 9 orders |
| *Demand mix at end item level (generic level)* | 31 variants (6) | 72 variants (3) | 10 variants (10) |
| *Total volume demand* | 1,153 keypads | 26,890 keypads | 44,035 bodies |
| *Av. volume demand at end item level (generic level)* | 37 keypads (192) | 373 keypads (8,963) | 4,404 bodies (4,404) |
| *Av. CV of demand at end item level* | 376% (168-412%) | 249% (59-400%) | 233% (30-412%) |
| *Av. CV of demand at generic level* | 328% (155-412%) | 96% (31-198%) | 233% (30-412%) |

The demand mix is first considered for each UoA. The highest number of variants was required for the EPP keypad and the lowest for the PB body - 72 compared to 10 variants respectively. This was expected, however the demand mix for the EPP keypads was not expected to be higher than that for the MA keypads (refer to Appendix 23 for a detailed discussion).

The average volume demand at end item level was much greater at 4,404 for PB bodies than it was for EPP keypads at 373. This was largely a reflection of the much higher demand mix for the EPP keypads although the higher total volume demand for the PB bodies will also have made a small contribution to this difference. The average volume demand at generic level was much higher for the EPP keypads than for the MA keypads. This was due to two factors:

- EPP keypads were demanded in much higher volumes overall,
- the number of MA generic keypads was double that for the EPP keypads.

Further, it should be considered that in the case of the MA keypads the generic keypad bodies (e.g. MA10, MA11, MA12) did not physically exist at any stage in the manufacturing process.

Surprisingly the demand variability (CV of demand) at end item level was not much lower for the PB bodies than for the EPP keypads - only 233% compared to 249% respectively. The explanation for this was related to the number of orders at end item level – about nine on average for both the EPP keypads and the PB bodies. In fact half of the ten stocked PB bodies were only subject to one or two orders over the study period and therefore exhibited a very high CV of demand, in excess of 300%. If these PB bodies were excluded, demand variability dropped to 97%.

The demand variability for EPP keypads was dramatically reduced when taken at the unconfigured, or generic, keypad level - 96% compared to 249% at the finished keypad level. So clearly keeping stocks at the generic level should have permitted the provision of a much lower safety stock than stocking at the finished item level.

***Summary:*** as expected the demand mix was higher for the EPP keypads than for the PB bodies - 72 compared to 10 variants respectively. The average volume demand at end item level was much greater at 4,404 for PB bodies than it was for EPP keypads at 373. This was largely because the demand mix for the EPP keypads was much higher. The average volume demand at generic level was much higher for the EPP keypads than for the MA keypads. Surprisingly the demand variability at end item level was not much lower for the PB bodies than for the EPP keypads, 233% compared to 249% respectively.

### *6.4.2 Demand Amplification*

The demand data, in terms of the promised due dates and quantities, presented in the previous section was used to measure the demand imposed on the manufacturing system. The manufacturing orders would have provided a very similar demand plot to the process schedules because manufacturing orders, covering only one operation, were scheduled in due date order, and each order was manufactured continuously until completed. Consequently it was decided to plot the process schedules only, since they reflected more closely the timing of demand on the particular manufacturing process.

The manufacturing process schedules were available to the operator at each work centre on PMCS (refer to Appendix 21 for details). The operator 'booked on' jobs as they were started and 'booked off' jobs as they were completed. Unfortunately the work centre schedules were not retrospectively available on PMCS, however the 'booking' dates were available. The 'booking on' dates were used because they accurately reflect the scheduled sequence and timing of jobs at each process and therefore any batching which may have occurred.

The demand amplification charts for the EPP keypads and MA keypads are shown in Appendix 24. The plots in each chart span the same weekly time buckets and use the same scale so the relative amplitude of demand can be easily compared. Separate charts were plotted for the plastic and steel EPP keypads since three times as many plastic keypads were demanded as steel keypads. This may have resulted in the pattern of replenishment of the unconfigured keypad stocks being quite different. Each chart showed the weekly demand for the EPP keypads, the keypad configuring schedule and the unconfigured keypad assembly schedule. Demand amplification was not evident in either of the charts for the EPP keypads when measured at a weekly level. The peaks in demand were similar in amplitude to the peaks in the process schedules.

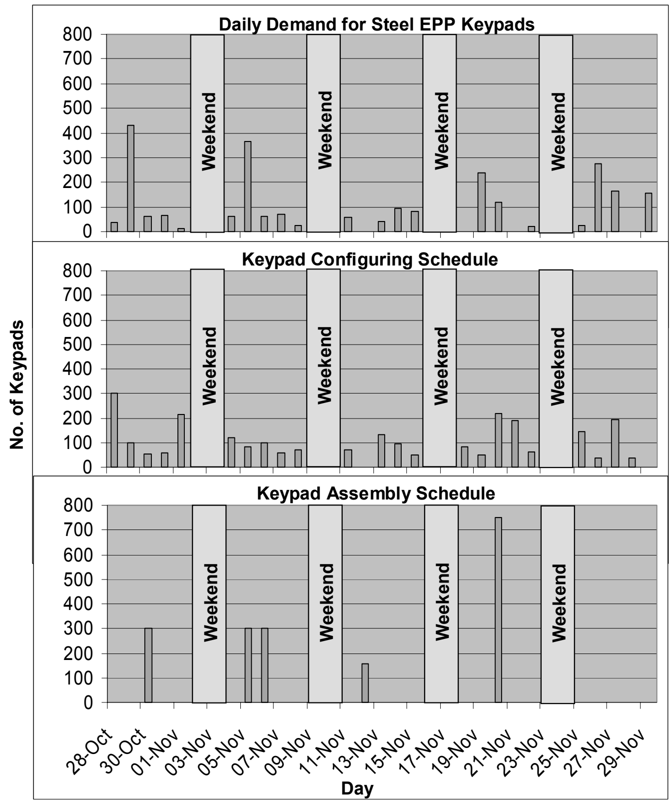



**Figure 6.3: Demand Amplification measured at a daily level for steel EPP keypads due between 28th October and 29th November '02**

EPp keypads were demanded on a daily basis rather than a weekly basis as was the case for both the MA keypads. Therefore, the daily demand amplification for the EPP keypads was plotted over a 5 week period from 28th October to 29th November as shown for the steel keypads in Figure 6.3. Even when the demand patterns were plotted at the daily level demand amplification was not evident in the keypad configuring schedules. However it was apparent in the keypad assembly schedules. For the plastic keypads, the demand amplification in the keypad assembly schedule was only slight - the peaks and troughs in the schedule were marginally more pronounced than the peaks and troughs in demand. However for the steel keypads the demand amplification was more evident - as illustrated in Figure 6.3. This was probably due to the fact that over this 5 week period the stocks of unconfigured steel EPP keypads were about double the stocks of plastic (as illustrated in Appendix 21) while the demand for steel EPP keypads was less than half the demand for plastic EPP keypads.

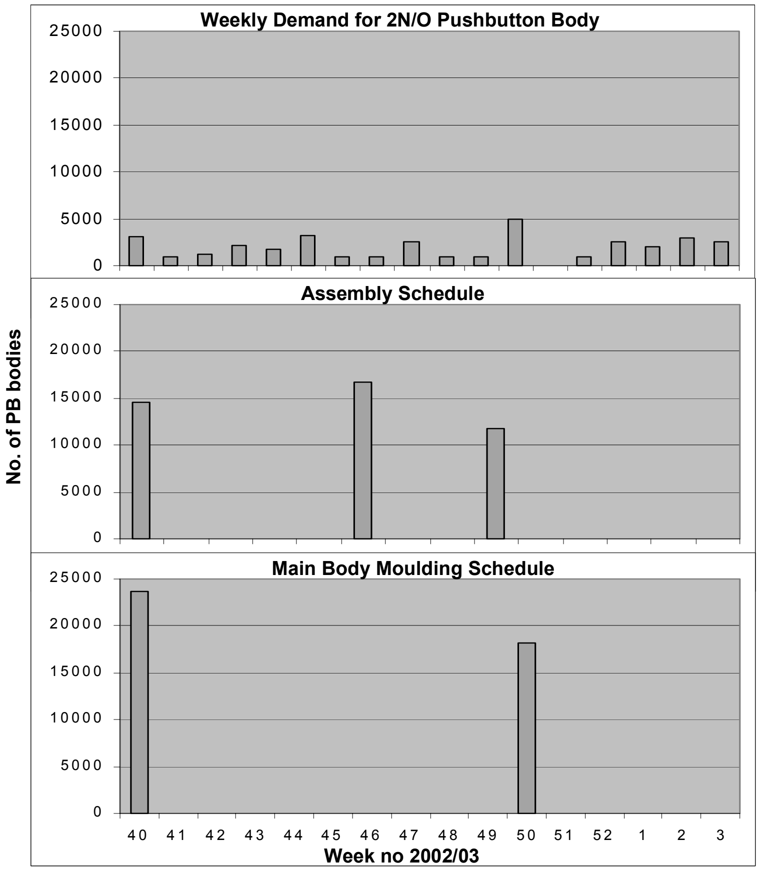



**Figure 6.4: Demand Amplification charts for the '2N/O' PB body**

The demand amplification chart for the standard PB body (2 N/O), shown in Figure 6.4, shows the weekly demand for the PB bodies, the PB bodies assembly schedule and the main body part injection moulding schedule. Both the assembly schedule and body moulding schedule show severe demand amplification where the peaks are, on average, about four times the amplitude of the peaks in demand. This is clearly due to high replenishment batch quantities at both the assembly and moulding processes.

The demand amplification chart for the MA keypads (shown and discussed in Appendix 24) illustrates that, with the exception of one incidence of batching, there was no evidence of demand amplification for the MA keypads.

***Summary:*** demand amplification was not evident in the assembly schedule for the MA keypads and neither was it evident in the EPP keypad configuration or assembly schedules - when measured at a weekly level. However, unlike the MA keypads, the EPP keypads were demanded on a daily rather than weekly basis. When the demand patterns were plotted at the daily level demand amplification was apparent in the EPP keypad assembly schedules particularly for the steel keypads. Severe demand amplification was evident in both the assembly schedule and body moulding schedule for the PB bodies.

### *6.4.3 Customer Service*

Three measures were used to monitor customer service - order lead-time, delivery performance and ex-stock availability. Unfortunately, data were unavailable to measure ex-stock availability in terms of the proportion of initial enquiries and orders for which the correct stock item was available. Therefore stock records (plotted in Appendix 21) for both the unconfigured EPP keypads and the PB bodies were used to indicate ex-stock availability. Data for the EPP keypad stock levels were sourced from the EPP Production Supervisor who recorded stock levels each morning and the PB body stock records were sourced from the MAPICS Transaction History module.

The unconfigured EPP keypad stock levels varied between 0.5 and 6.2 weeks forward cover (on the basis of the average demand over the study period) and no stock outs were recorded. Further it was known that there were no enquiries only firm orders with a non-negotiable lead-time and that the delivery performance on these orders was extremely high, 98% on time in full. Therefore, it was fair to assume that ex-stock availability for the unconfigured keypads was no less than 98%.

Stock outs were recorded for three of the PB bodies and this alone reduced delivery reliability to 94%. Three PB body orders were delivered short and an analysis of the stock levels suggests that in all 3 cases this was due to insufficient stocks being available. Also 6 orders were delivered late and in two cases this appears to have been due to stock outs. Further, in addition to orders, PB bodies were subject to enquiries for which the ex-stock availability was not recorded. Therefore it was fair to conclude that the ex-stock availability for the PB bodies was at best 94% and therefore lower than for the EPP unconfigured keypads.

Neither order lead-time nor delivery reliability to the customer were measured by Dewhurst during the study period. However NCR measured the delivery performance of the EPP keypads and according to the Keypads Account Director a late delivery was an ‘event’. Also it was extremely rare for MA keypads to be delivered late because in the words of the NCR Business Administrator 'a safety margin is normally allowed when specifying the due-to-be-delivered date'. Finally the PB bodies were despatched ex-stock so delivery performance should not have been an issue.

**Table 6.6: The order lead-time and delivery reliability measures for all UoA.**

| *Measure* | *MTO (MA Keypads)* | *FPp (EPP Keypads)* | *MTS (PB Bodies)* |
|---|---|---|---|
| ***No. of orders assessed*** | 45 | 598 | 89 |
| ***Standard quoted lead-time*** | 3 wks | 1 wk (5 wkg days) | 1 wk |
| ***Order Lead-time*** | | | |
| ***Av. Promised order lead-time*** | 3.8 wks | 1.2 wks (6 wkg days) | 12.6 wks (2.8wks excl. Dupar) |
| ***Av. Actual order lead-time*** | 2.8 wks | 0.6 wks (3 wkg days) | 11.4 wks (2 wks excl. Dupar) |
| ***Av. Leadtime prior to factory order release*** | 7 hours | 0.5 hours | N/a |
| ***Delivery Reliability*** | | | |
| ***OTIF (full order delivered by due date)*** | 36 (80%) | 586 (98%) | 80 (90%) |
| ***OT (part of order delivered by due date)*** | 37 (82%) | 590 (99%) | 83 (93%) |
| ***IF (full order delivered)*** | 44 (98%) | 594 (99%) | 86 (97%) |

To determine the order lead-time and delivery reliability measures both promised and actual *ex-works* dates were required. Ex-works dates rather than delivery-to-the-customer dates were used because all Dewhurst's customers were responsible for arranging transport of the goods from the Dewhurst factory. Therefore Dewhursts responsibility ended upon despatch of the order. The *promised* and *actual* order lead-times were measured from receipt of the customer order to *promised* and *actual* ex-works dates respectively. The evidence for all dates was gathered from the MAPICS Customer Order Module.

The order lead-time and delivery reliability measures for each UoA are presented in Table 6.6. The standard quoted lead-time for the EPP keypads was 5 working days equivalent to 1 week, however the average promised lead-time was 1.2 weeks. The promised lead-time for EPP keypads was always what the customer (NCR) requested. This suggested that, on average, NCR did not require a lead-time as short as 1 week. Further, the actual order lead-time achieved was only 0.6 weeks, equivalent to 3 working days, demonstrating that Dewhurst were delivering keypads to NCR with double the responsiveness requested by them.

As expected the order lead-time achieved for the EPP keypads was only about one fifth of that achieved for the MA keypads. This was in part due to the different approach to manufacturing but also to the more responsive approach to order processing and manufacturing planning used for the EPP keypads (as explained in sections 6.3.2 and 6.3.3). On average MA keypad orders required 7 hours in Order Processing before the manufacturing orders were released, whereas EPP keypads orders only required 0.5 hour. Further, released MA keypad manufacturing orders were downloaded three times each day to PMCS which ensured an average delay of 4 hours between order release by OPD and availability for manufacturing. Released EPP keypad manufacturing orders by-passed PMCS to ensure a rapid response from production. Hard copies of the EPP manufacturing orders were passed to Production, via the Keypad Demand Manager, typically by 10.30am - only 1 hour after the manufacturing order was released.

The actual order lead-times for the PB bodies supplied ex-stock was 11.4 weeks, against a standard quoted lead-time of 1 week. This was, at least in part, explained by the fact that two thirds of the orders were for Dupar (the Dewhurst Canadian subsidiary) who requested an 18 week lead-time on average. Excluding Dupar orders reduces the lead-time to 2 weeks still significantly longer than the lead-times for the EPP keypad.

Delivery reliability was very high for the EPP keypads, 98% of orders were delivered On Time In Full. Only 4 out of the 598 orders were delivered short and 8 orders delivered late. The high delivery reliability was no doubt due to high ex-stock availability of the unconfigured keypad (and the keytips) together with the highly responsive approach to order processing, manufacturing planning and keypad configuration. As expected delivery performance for the MA keypads was lower at 80%. Only 1 order out of 45 orders was delivered short however 8 orders were delivered late. The most likely explanation for this poor delivery reliability lay in the extremely high demand variability for the MA keypads far higher than for the finished

EPP keypads – 376% compared with 249%%. This resulted in highly variable demand on the MA keypad assembly cell as the capacity utilisation measure demonstrates (refer to section 6.4.6). Although the average utilisation is low at 27% this assumes the maximum labour level of 2 men was always available. However in practice it was probably only occasionally that 2 men worked at this cell simultaneously. Therefore the capacity utilisation figures for the MA keypad cell were probably much higher (almost double) but as variable as the graph in Appendix 27 indicates.

***Summary:*** ex-stock availability as indicated by stock records was higher for EPP keypads than for PB bodies. As expected the order lead-time achieved for the EPP keypads was only one fifth of that achieved for the MA keypads. Further, the actual order lead-time achieved for EPP keypads was only 0.6 weeks, on average double the responsiveness requested on a day to day basis by NCR, the EPP keypad customer. Delivery reliability was very high for the EPP keypads, 98% of orders were delivered On Time In Full and as expected the delivery performance for the MA keypads was lower at 80%.

### *6.4.4 Product Modularity*

The relative degree of modularity exhibited by the three products studied was assessed using evidence gathered from interviews with the Design Project Leader, the Process Engineering Manager and a Process Engineer. This interview evidence was corroborated by the indented BOMs, which were extracted from the MAPICS MRP system. Simplified versions of the indented BOMs are illustrated in Figure 6.5.

The relationship between the functional architecture and the physical architecture of both the EPP and MA keypads was quite transparent. The keytips performed a particular function therefore each keytip was a module - available in many variants which could be combined to provide numerous keypad configurations (or layouts). Also there were no incidental interactions between the keytips therefore the keytips were highly modular.

Behind the keys the keypad body displayed a lesser degree of modularity with a number of components providing the electronic keypad functionality and the mechanism for the keying operation. These components were not available in many variants, if at all, and they were not combined to produce different keypad body variants.

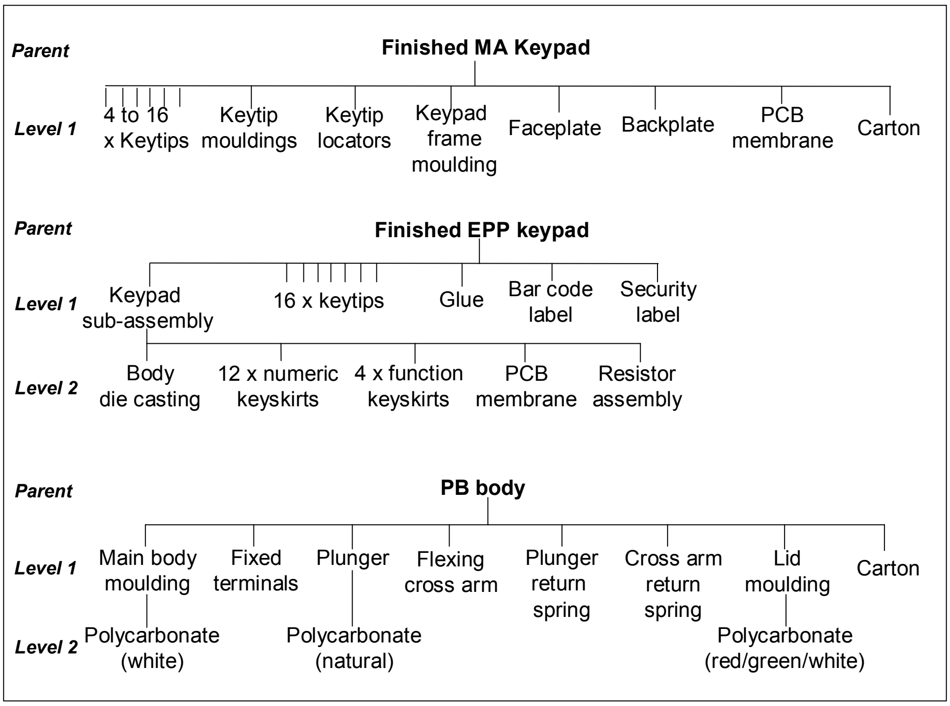



**Figure 6.5: Indented BOM showing the main components at all six levels**

Interestingly the EPP keypad (unlike the MA keypad) was specifically designed for 'last minute configuration' or FPp. However the EPP keypads were no more modular than the MA keypads – the components in the EPP keypad body were not physically divided, to reflect the functional elements of the design, any more than the MA keypad components. The modularity displayed by the EPP keypad was an incidental characteristic rather than being the result of a deliberate product design effort.

There was a clear relationship between the functional and the physical architecture of the PB body. All the components corresponded to a functional element. The pair of contacts were disabled for an indicator and configured for a switch (normally open, normally closed or changeover). Illumination terminals were required if the PB body was illuminated. Power terminals were always required and available in a number of variants. It is problematic to compare the modularity of two different products and in this study the hypothesis does not call for a comparison of the MTS and FPp products with respect to product modularity. However the PB body does appear to be more modular than the EPP keypad since each component corresponds to a functional element.

The type of modularity exhibited by the EPP keypads was ‘component swapping’ modularity (Pine, 1993). Different components, in this case keytips, were paired with the same basic product, an unconfigured keypad, to produce variety in the finished product.

***Summary:*** The EPP keypads and MA keypads exhibited the same degree of modularity. Each keytip performed a particular function and there were no incidental interactions between them therefore the keytips were highly modular. The EPP and MA keypad bodies displayed a lesser degree of modularity with a number of components providing the electronic keypad functionality and the mechanism for the keying operation. Interestingly although the EPP keypad (unlike the MA keypad) was specifically designed for ‘last minute configuration’ (or FPp) its modularity was an incidental characteristic rather than being the result of a deliberate design effort.

### *6.4.5 Product Standardisation*

The level of product standardisation was indicated by two measures: the proportion of components common to all variants in the UoA and the *degree of commonality index*. The full indented BOMs (sourced from the MAPICS BOM module) were analysed for products within each of the UoA (refer to Appendix 25 for a full list of analysed parts). In accordance with the scope of the study both the EPP and MA keytip components were excluded from this analysis. Unfortunately the BOMs for 6 MA keypad variants were not available because they were classed as ‘specials’ and used configurable BOMs. ‘Specials’ were MA keypads which used standard keypad bodies, but were subject to one small order. Therefore their exclusion from this analysis had only a minor impact on the product standardisation measures.

The product standardisation measures are summarised in Table 6.7. The number of end items for each UoA was the number of variants subject to demand during the study period, or the demand mix. The number of distinct components in each end item was very similar for the two keypads (around 30 components). However the PB body contained, on average, 13 distinct components.

Only the polycarbonate for the main body moulding was common to all 10 variants of the PB bodies. Similarly only the keytip moulding body component was common to all 31 variants of the MA keypads. In contrast 14 of the EPP keypad components were common to all the variants (all body components). In fact the only EPP keypad body components that *weren't* common were the keyskirts, a reflection of the variety in the keytip material and depth. Naturally no keytips were common across either the EPP or MA keypads.

**Table 6.7: Product standardisation measures compared for the UoA**

| *Measures* | *MTO (MA Keypads)* | *FPp (EPP Keypads)* | *MTS (PB Bodies)* |
|---|---|---|---|
| *No. of end items (generic level)* | 31 variants (6) | 72 variants (3) | 10 variant (10) |
| *Average no. of distinct components analysed per end item (range)* | 31 (15-38) | 29 (23-35) | 13 (7-17) |
| *No. of common components (proportion)* | 1 (3%) | 14 (48%) components in key body | 1 (8%) body moulding poly carbonate |
| *Degree of commonality index* | | | |
| *BOM Level 1 components* | 6 (24%) (body assembly) | 5 (7%) (keytips) | 5 (45%) (body assembly) |
| *BOM Level 2 components* | 3 (14%) (keytips) | 57 (79%) (body assembly) | 7 (70%) (moulded parts) |
| *Over both level 1 and 2* | 5 (15%) | 10 (14%) | 5 (50%) |

The degree of commonality index was measured for two sets of components, the BOM level 1 and BOM level 2 components. In the case of the MA keypads the BOM only had one level since the components were all assembled in one operation. Since the keytips were assembled first, they were dropped to a notional BOM level 2. This enabled comparisons to be made between keytip and body component commonality in MA and EPP keypads. The commonality index measures are summarised in Table 6.7 and a detailed explanation of how they were calculated is presented in Appendix 26.

Overall the EPP and MA keypads exhibited a very similar degree of component commonality - 14% and 15% respectively. However the source of the commonality was quite different. The degree of component commonality in the keypad body parts was much greater for the EPP keypad than the MA keypad - 79% compared to 24%. While the degree of component commonality in the keytips was higher for the MA keypad than the EPP keypad - 14% compared to7%.

Lack of commonality in the MA keypad body parts was due to two sources of variety not present for the EPP keypad. Firstly, the MA keypads were demanded in three different sizes - 16 keys, 12 keys and 4 keys. Secondly, a special range of MA keypads had been developed for Fujitsu (Spain). Historically the biggest customer, and these keypads incorporated a completely different body design with special keytips. Interestingly over the study period Fujitsu only placed 5 orders for these keypads accounting for only 5% of the MA keypad volume demand.

Lack of commonality in the EPP keytips was due to high variety in keytips, even in terms of their material. The MA keytip material was standardised as brushed stainless steel whereas the EPP keytips were available in plastic or steel. Further the steel EPP keytips were subject to variety of a similar magnitude to that found in the MA keytips.

***Summary:*** a much greater proportion of the EPP keypad components was common to all variants than MA components - 48% compared with 3% respectively. All the common components were keypad body parts. Overall the EPP and MA keypads exhibited a very similar degree of component commonality - 14% and 15% respectively. However the source of the commonality was quite different - commonality in the keypad body parts was greater for the EPP keypads whereas commonality in the keytips was higher for the MA keypads.

### *6.4.6 Excess Capacity*

No production record was made of downtime due to the lack of demand defined as excess capacity. Therefore, it was not possible to measure excess capacity directly. Instead the ratio of actual output to design capacity (capacity utilisation) was used as an indication of excess capacity – the lower it was the more likely excess capacity existed.

Over the study period Dewhurst was not measuring capacity utilisation. Although the Capacity Resource Planning module calculated available capacity and capacity overload at each cell, these calculations were based on inaccurate labour levels and cycle times. Capacity utilisation was calculated for this study using the following formula:

$$\text{Weekly Cell Capacity Utilisation} = \frac{\text{Actual Cell Output (man hours)}}{\text{Cell Design Capacity (man hours)}}$$

where

Actual Cell Output = weekly cell output x unit processing time
Cell Design Capacity = available labour level x weekly operating hours

The production cells engaged in the manufacture of the PB bodies also manufactured many other products. Unfortunately neither the total output figures, nor a breakdown of labour dedicated to PB body production, were available. Therefore it was not possible to measure capacity utilisation for this UoA.

The production capacity of the EPP manufacturing cell was extremely flexible because, in the words of the Production Engineering Manager:

> *'the EPP keypad is a relatively simple product requiring manual assembly processes which can be broken down into small simple operations. An EPP assembly line can be rapidly established and people can be quickly trained to man the line, even temporary employees.'*

In fact between 14$^{th}$ October and 20$^{th}$ December thirteen temporary staff were assigned to the NCR production cell and all were dedicated to the manufacture of the EPP keypad. A full account of the changes in EPP labour levels is detailed in Appendix 22. The maximum available labour levels were used to calculate design capacity for the EPP and MA keypad assembly cells. In the case of the MA cell a maximum of 2 men were available, however in practice it was probably only occasionally that 2 men worked at this cell simultaneously (during my visits I only ever observed one man). Therefore the capacity utilisation figures for the MA keypad cell were an underestimate in comparison to those for the EPP keypad cell.

Cell output for a given week was calculated using job booking-on times rather than booking-off because they were known to be more reliable. The unit processing times for both the keypads (detailed in Appendix 22) were sourced from the MAPICS BOM module. These times were validated through interviews with the respective production supervisors, all of whom had many years experience with these types of processes.

Processing times for the EPP configuring cell remained constant at 4.5 man minutes, despite the introduction of a gluing machine during November 2002. However processing times for the assembly of the unconfigured EPP keypad changed over the study period, as Flow Process Charts (recorded by the production team) testified. This was due to changes in the method of moving the work piece down the assembly line as detailed in Appendix 22. The conveyor belt was found to be too restrictive. Operators complained that it was too stressful when the pace of work was dictated by the speed of the belt. Removing the conveyor belt reduced unit processing times from 8.5 to 5.5 man minutes and - with further work on balancing the operations - the processing time was reduced further to 4.5 man minutes by 20th January.

**Table 6.8: Capacity measures for the EPP and MA production cells for the study period 30th September 2002 to 31st January 2003.**

| Cell | Average Values | | | | | CV |
|---|---|---|---|---|---|---|
| | Labour levels | Weekly Design Capacity (man hours) | Processing Time (man minutes) | Weekly Output (man hours) | Weekly Capacity Utilisation | |
| **EPP Keypad Assembly** | 7.7 | 288 | 6.8 | 212 | **71%** | 38% |
| **EPP Keypad Configuring** | 4.9 | 185 | 4.5 | 115 | **62%** | 51% |
| **MA Keypad Assembly** | 2 | 75 | 15 | 20 | **27%** | 111% |

Capacity utilisation calculations are summarised in Table 6.8 (refer to Appendix 27 for details). The design capacity of the two EPP keypad cells appears different because its expressed in man hours. Actually, design capacity of the assembly cell was very similar to that of the configuration cell - 68 keypads per hour compared with 66.

Average weekly capacity utilisation for the stock-driven assembly of the keypads was higher (and less variable) than that demonstrated by the order-driven keypad configuration, as demonstrated by the charts in Figure 6.6. Capacity utilisation for the keypad assembly cell was on average 71% compared to 62% for the keypad configuration cell. The variability (CV) of the weekly capacity utilisation was only 38% for keypad assembly compared to 51% for keypad configuration.

At the beginning of 2003 the volume of keypads assembled was very low with only 24 keypads assembled over weeks 2 and 3 (as the capacity utilisation chart in Figure 6.6 indicates). If the capacity utilisation measures for weeks 2 and 3 were excluded the *average* capacity utilisation for keypad assembly increased to 80% and the CV dropped to 18%.

It is evident from the charts in Figure 6.6 that capacity utilisation for the EPP configuring cell rose above 100% during weeks 48, 49 and 4. During these weeks overtime was employed in response to peaks in demand which were illustrated by the demand amplification charts in Appendix 24.

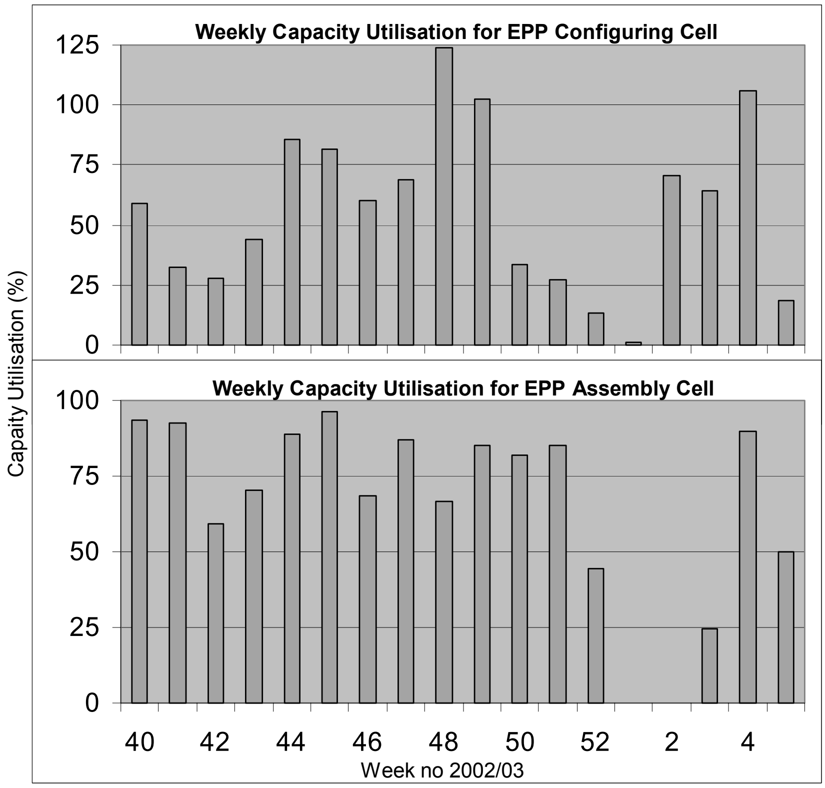



**Figure 6.6: Charts showing the variation in weekly capacity utilisation for the EPP keypad cells**

The average weekly capacity utilisation measured for the order-driven MA keypad assembly cell was 27%. This was much lower than for either of the EPP keypad cells. The CV also suggested it was much more variable, however, (as discussed in Appendix 27) this is not a reliable measure.

***Summary:*** in the absence of downtime records the capacity utilisation measure was used to indicate excess capacity. Average weekly capacity utilisation for the stock-driven assembly of the EPP keypads was significantly higher and less variable than that demonstrated by the order-driven keypad configuration process. Capacity utilisation for the keypad assembly cell was 71% compared to 62% for the keypad configuration cell and the variability (CV) was 38% compared to 51% respectively. Capacity utilisation for keypad assembly rose further to 80% and the CV dropped to only 18% if weeks 2 and 3 (when an unusually low volume was assembled) were excluded from the measure. This suggested that it was at the postponed configuration process where excess capacity was likely to be the greatest.

### *6.4.7 Throughput Efficiency*

The value adding activities at Dewhurst were the *operations* identified in the flow process chart in Table 6.1. Throughput efficiency was measured for all the assembly processes in the three UoA. The injection moulding of the PB body plastic components was excluded because it was a completely different type of process - equipment driven rather than labour driven - and therefore throughput efficiency comparisons would not be meaningful.

Value added times for each order were calculated from the cycle times which are detailed in Appendix 22. In the previous case study (at BC) elapsed time was measured to booking into warehouse therefore this was the favoured measure here (for cross-case comparison purposes). However, at Dewhurst elapsed time was measured from the date the manufacturing order was released into the factory to the despatch date. This was because the booking into warehouse data was unavailable for the order driven processes - EPP configuration and MA assembly. For the EPP keypads this made little difference to the throughput efficiency measure because on average the *total time* between completion of manufacturing and despatch was only 3% of the elapsed time. For the MA keypads this may have had a significant impact on the throughput efficiency measure which, as a result, could be underestimated. All the dates were sourced from MAPICS and verified through interviews with the Planning Manager and Systems Manager.

**Table 6.9: Throughput efficiency measures for the UoA.**

| *Average Values* | | *Order Driven* | | *Stock Driven* | |
|---|---|---|---|---|---|
| | | ***MA Keypad Assembly*** | ***EPP Keypad Configuration*** | ***EPP Keypad Assembly*** | ***PB body Assembly*** |
| ***No. of orders assessed*** | | 38 | 596 | 61 | 20 |
| ***Value added time*** | | 7.9 hrs (1 wkg day) | 2.6 hrs (0.3 wkg day) | 20.7 hrs (2.7 wkg day) | 30.5 hrs (4.1 wkg day) |
| ***Elapsed time prior to start of manufacturing*** | | 2.8 wkg day | 2.6 wkg day | 9.6 wkg day | 12.5 wkg day |
| ***Total Elapsed Time*** | | 21.1 wkg day | 3.0 wkg day | 17.5 wkg day | 23.1 wkg day |
| ***Throughput Efficiency*** | ***Average*** | ***6.5%*** | ***11%*** | ***27%*** | ***17%*** |
| | ***CV*** | 114% | 167% | 93% | 125% |
| | ***Range*** | 0.04 – 33% | 0.2 – 98% | 1.5 – 97% | 0.3 – 72% |
| | ***Notes*** | (including time in the finished goods warehouse) | | (excluding time in the finished goods warehouse) | |

A summary of the throughput efficiency measures is presented in Table 6.9. Measures for the two EPP processes are compared first - the order driven keypad configuration and the stock driven keypad assembly. Contrary to predictions the throughput efficiency was higher for the stock driven EPP assembly than it was for the postponed configuration - 27% compared to 11%. This was in spite of the fact that manufacturing lead-times for the postponed configuration process were considerably shorter than for the keypad assembly process - 3 compared to 17.5 working days respectively. There were two explanations for the unexpectedly low throughput efficiency at the postponed configuration process:

- the size of the customer orders for configured keypads were on average much smaller than the size of the EPP assembly manufacturing orders – 45 compared with 520 respectively

- the keypad configuration manufacturing lead-time was extended (by 85% of the lead-time) by queuing caused by capacity restrictions at this process. However, the order lead-times required by the EPP customer, NCR, were being reliably satisfied as illustrated by the customer service measures in section 6.4.3. Therefore it appeared that a shorter manufacturing lead-time - or higher throughput efficiency - was not needed.

In addition to the throughput efficiency at the EPP configuration process being low it was also highly variable from order to order (almost twice as variable as at the EPP assembly process) as the CV of 167% demonstrates. The main factor driving the variability in throughput efficiency was the customer order sizes which varied from 1 to 840 configured keypads.

The most striking difference between EPP assembly and the postponed configuration was - not the throughput efficiencies - but the manufacturing lead-times. Keypad configuration was clearly more responsive with a manufacturing lead-time equivalent to only 17% of the keypad assembly lead-time.

In general there was a trend for throughput efficiencies at the two EPP cells to fall over the study period due to reductions in cycle times which were not matched by reductions in manufacturing lead-times.

MA keypad assembly and PB body assembly also demonstrated throughput efficiencies contrary to expectations. However the throughput efficiency measure for the MA keypads was probably grossly underestimated, in comparison to the PB body measure, as explained earlier.

***Summary:*** Contrary to expected results the throughput efficiency was higher for the stock driven EPP assembly than it was for the order driven configuration - 27% compared to 11%. This was in spite of the fact that manufacturing lead-times for the postponed configuration process, were considerably shorter than for the keypad assembly process - 3 compared to 17.5 working days respectively. There were two explanations for the unexpectedly low throughput efficiency at the postponed configuration process. Firstly the size of the customer orders for configured keypads were much smaller than the EPP assembly manufacturing orders - 45 compared with 520 respectively. Secondly the keypad configuration manufacturing lead-time was extended (by 85% of the lead-time) by queuing at this process.

### *6.4.8 The Production Variety Funnel*

A PVF central to the conceptual model of FPp was plotted for each UoA, as shown in Figure 6.7. The BOM data previously used for the product design measures and originating from the MAPICS MRP system was used. The allowed process lead-times, measured in working days, were taken from the MAPICS system. Manufactured parts are printed on the vertical axis of the PVF, such as the unconfigured keypads. Components issued from stock are printed on the horizontal axis such as keytips.

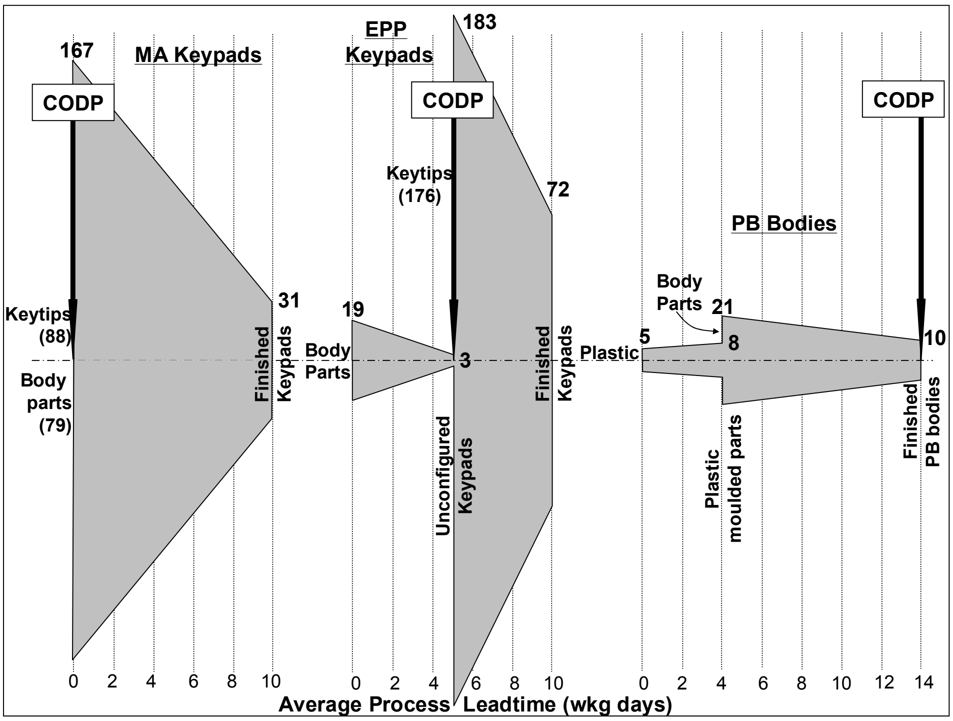



**Figure 6.7: The Production Variety Funnels**

The PVF is a simple but different shape for each UoA. For EPP keypads it is the typical mushroom shape commonly associated with FPp. In fact there are only three generic or unconfigured keypads at the CODP. However a high number of other components supplied into the postponed configuring process - keytip variants - must be stocked (refer to the section 6.3.2 on inventory management for a full explanation of why stocks are required). There were 176 keytip variants compared with only 72 finished EPP keypad variants. Moreover, although the theoretical potential number of finished EPP keypads was much greater than 72, this product was supplied exclusively to one customer and therefore the actual number of finished items is unlikely to change significantly. When the steel keytip keypads are phased out (as planned by NCR) the number of keytips required will be dramatically reduced. Of the 176 keytips stocked only 22 are plastic keytips which cover 35 finished keypad variants.

The PVF for MA keypads is an ‘A’ shape (when turned through 90 degrees with the end item uppermost), typical of a MTS product. However the MA keypad was MTO as the CODP indicates. The reason for not using the MTS approach was three fold:

- Firstly, MA keypads were only occasionally demanded in one of the three standard specifications. Almost all the MA keypad orders were for highly customised keypads and therefore unique to the particular customer. In fact the potential variety in the finished MA keypads was much greater than the PVF shows. This is in contrast to the PVF for the EPP keypads, which shows the full variety likely to be demanded.

- Secondly, the number of repeat orders for MA keypads was very low, on average only 1.5 orders were placed for each MA keypad item over the 4 month study period.

- Thirdly, it appeared that the market accepted the 3 week lead-time readily and there was no need for a more responsive supply.

FPp was not a suitable approach for the production of the MA keypads. This can be illustrated by splitting the manufacturing process into three consecutive stages: configuring the keytips, assembling the keypad body and packing. At no stage does the number of distinct items drop below the number of finished keypads, 31. Configuring the keytips was the main differentiating process and once this was completed the number of distinct sets of keytips was the same as the number of end items. Assembling the body and the packaging did not further differentiate the product.

The variety of components required to make the PB bodies was much less than for the keypads. This was because each body required less than half the distinct components required for the keypads and the finished bodies were demanded in fewer variants. The PVF for the PB bodies is the ‘A’ shape commonly associated with MTS. However more variety in the components is normal to justify a finished stock. There were only 21 distinct components in the 10 PB bodies as a result of a deliberate effort to standardise the components across the different variants.

## 6.5 CASE ANALYSIS

In this section the results of the case analysis are presented: first the major flaws in the FPp application are discussed, and second the findings are compared with the hypotheses.

### *6.5.1 Not the Planned Ideal FPp Application*

Originally it was planned that the EPP keypad would (after a very short time) be largely supplied in the plastic keytip variant and the steel keytip variant would be supplied in minimal volumes, if at all. Further it was envisaged that the number of keytip colour configurations would be limited to a handful, say five, and that *only* stocks of these keypad variants would be maintained. The principal benefit being that only the laser marking of the legend on the keytips would be performed to specific customer orders. Therefore no components stocks would be required and the keypads could be supplied on a very short lead-time.

However, the demand for EPP keypads was not as NCR forecasted in three respects:

- Firstly the steel keytip keypads continued to be demanded in very significant volumes forcing Dewhurst to maintain a stock of the unconfigured steel keypad. In fact over the four-month study period the steel tipped EPP keypad accounted for over a quarter of the volume.
- Secondly, the plastic keypad was demanded in eighteen - rather than five - different keytip colour configurations.
- Thirdly, the total EPP keypad sales volume was heavily overestimated.

The operational implications were that the CODP had to be located further upstream than planned and the unconfigured keypads together with many variants of the keytips (plastic and steel) had to be stocked. In addition - rather than merely laser marking - gluing and populating of the keytips onto the keypads also had to be performed to customer order. This reduced the potential for lead-time and component stock reduction. Finally the overestimated EPP keypad sales forecasts lead to excessive unconfigured keypad stocks.

Indeed it can be argued that given the low value adding time to manufacture the unconfigured keypads (4.5 minutes) it was possible for Dewhurst to assemble the keypads entirely to order. This would still require the application of FPp but the CODP would be moved upstream so only the keytips are manufactured to stock. There was no possibility of making the keytips to order because they required a long manufacturing lead-time.

The main implication of moving the CODP was that the buffer stock of unconfigured keypads would be lost. This protected the unconfigured keypad assembly process from the high demand variability - both in terms of volume demand variability at finished keypad level (or varying demand mix) and at generic keypad level. Without the generic keypad buffer stock the assembly of the unconfigured keypad – as well as the gluing and populating of the keypads - would require excess capacity to cope with the high demand variability.

### *6.5.2 Hypotheses Testing*

All six hypotheses were fully tested in the Dewhurst case study and the findings were largely as predicted by the six hypotheses. However two hypotheses were challenged in part (H5 and H6).

***What is the demand profile of products selected for manufacture under FPp?***

> **H1: Products are selected for manufacture under FPp rather than MTS when they exhibit high demand mix, high demand variability and low volume demand at finished product level.**
>
> **H2: Products are selected for manufacture under FPp rather than MTO/ETO when they exhibit high volume demand at generic product level.**

The findings support both hypotheses H1 and H2. The EPP keypads manufactured under FPp were demanded in seven times as many variants as the MTS PB bodies - 72 compared to 10 variants. As a result the average demand volume at finished item level was much lower for the FPp EPP keypads than the MTS PB bodies - 373 compared to 4404 items.

As expected the average demand variability at finished item level was higher for the FPp EPP keypads than for the MTS PB bodies. However the difference in variability was only marginal 249% compared to 233%. The explanation for this was related to the number of orders at end item level – about nine on average for both the EPP keypads and the PB bodies. In fact half of the ten stocked PB bodies were only subject to one or two orders over the study period and therefore exhibited a very high CV of demand, in excess of 300%. If these PB bodies were excluded demand variability dropped to 97%.

As predicted by hypothesis H2 the average volume demand at generic level was much higher for the FPp EPP keypads than for the MTO MA keypads - 8,963 compared to 192 keypads. This was due to two factors:

- the number of MA generic keypads was double that for the EPP keypads
- EPP keypads were demanded in much higher volumes than the MA keypads.

Further, it should be considered that in the case of the MA keypads the generic keypad bodies did not physically exist at any stage in the manufacturing process.

***What is the impact on customer service of FPp?***

**H3: FPp considered as an alternative to MTS increases ex-stock availability.**

**H4: FPp considered as an alternative to MTO/ETO reduces order lead-times and increases delivery reliability but introduces demand amplification**

The findings support H3, however data were unavailable to measure *ex-stock availability* in terms of the proportion of *enquiries and orders* for which the correct stock item was available. Therefore stock records for both the generic EPP keypads (subject to FPp) and the PB bodies (subject to MTS) were used to indicate ex-stock availability. No stock outs were recorded for the generic EPP keypads. Further, there were no *enquiries* for EPP keypads, only firm orders with a non-negotiable lead-time for which the delivery performance was extremely high - 98% on time in full. Therefore, it was fair to assume that ex-stock availability was no less than 98% and most probably 100%.

Stock outs were recorded for three of the MTS PB bodies and this alone reduced delivery reliability to 94% on time in full. Unlike the EPP keypads PB bodies were subject to *enquiries* for which the ex-stock availability was not recorded. Therefore it was fair to conclude that ex-stock availability for the PB bodies was at best 94% and therefore lower than for the EPP unconfigured keypads.

The findings fully supported hypothesis H4. Demand amplification was measured at a weekly level for FPp (EPP keypads) and MTO (MA keypads) but it was not detected for either approach. However, the EPP keypads subject to FPp were demanded on a daily basis, rather than a weekly basis, and at this level demand amplification was detected for the FPp orders. Demand amplification was found in the assembly schedules for the unconfigured EPP keypads, particularly for the steel keypads. These findings support hypothesis H4 showing that applying FPp introduced a degree of demand amplification which did not exist for the MTO approach. In addition severe demand amplification (measured at a weekly level) was found in both the assembly and body moulding schedules for the MTS PB bodies.

As expected the order lead-time achieved for the EPP keypads (subject to FPp) was only one fifth of that achieved for the MA keypads (subject to MTO). In fact the order lead-time achieved by FPp was only 3 working days, on average double the responsiveness requested on a day to day basis by the customer. As expected the reduced order lead-time achieved by FPp was in part because the unconfigured EPP keypads were manufactured speculatively to stock rather than to order. However a more responsive approach to order processing and manufacturing planning also contributed to the reduction. On average the MA keypad orders required 11 working hours between customer order receipt and availability for manufacture whereas the EPP keypad orders only required 1.5 hours.

Delivery reliability was very high for the EPP keypads, 98% of orders were delivered On Time In Full. Only 4 out of the 598 orders were delivered short and 8 orders delivered late. The high delivery reliability was no doubt due to the high ex-stock availability of the unconfigured keypads (and the keytips) together with the highly responsive approach to order processing and keypad configuration. As expected delivery performance for the MA keypads was lower at 80%. Only 1 order out of 45 orders was delivered short however 8 orders were delivered late. The most likely explanation for this poor delivery reliability lay in the extremely high demand variability for the MA keypads far higher than for the finished EPP keypads – 376% compared with 249%. This resulted in highly variable capacity utilisation at a cell where capacity was not flexible.

***What are the product design implications of applying FPp?***

**H5: Product families subject to FPp will have a higher level of standardisation and modularity than product families subject to MTO/ETO**

The findings only partially supported hypothesis H5. As predicted the EPP keypads exhibited a higher level of standardisation than the MA keypads. A much greater proportion of EPP keypad components were common to all variants than MA keypad components (48% compared with 3%) and this was due to a single generic body design serving the full range of EPP keypads (with the exception of a single variable component). Overall the EPP and MA keypads exhibited a very similar degree of commonality index - 14% compared with 15% respectively. However the source of commonality was quite different - commonality in the keypad body parts was higher for the EPP keypads whereas commonality in the keytips (the configuring components) was higher for the MA keypads.

Contrary to H5 the EPP keypads and MA keypads exhibited the same degree of modularity. Each keytip performed a particular function and there were no incidental interactions between them therefore the keytips were highly modular. The EPP and MA keypad bodies displayed a lesser degree of modularity with a number of components providing the electronic keypad functionality and the mechanism for the keying operation. Interestingly the EPP keypad (unlike the MA keypad) was specifically designed for 'last minute configuration' or FPp. However the EPP keypads were no more modular than the MA keypads – the components in the EPP keypad body were not physically divided, to reflect the functional elements of the design, any more than the MA keypad components. The modularity displayed by the EPP keypad was an incidental characteristic rather than being the result of a deliberate product design effort.

***What are the manufacturing planning and scheduling implications of applying FPp?***

**H6: Capability of the postponed transformation process to respond to high demand variability requires excess capacity and high throughput efficiency**

The findings only partially support hypothesis H6. As predicted the findings showed that it was at the postponed configuration process that excess capacity was likely to be greater. Average weekly capacity utilisation for the stock-driven assembly of the EPP keypads was significantly higher and less variable than that demonstrated by the postponed configuration process. Capacity utilisation for the keypad assembly cell was

71% compared to 62% for the keypad configuration cell and the variability (CV) was 38% compared to 51% respectively. Capacity utilisation for keypad assembly rose further to 80% and the CV dropped to only 18% if weeks 2 and 3 (when an unusually low volume was assembled) were excluded from the measure.

The throughput efficiency was higher for the stock driven EPP assembly than it was for the postponed configuration - 27% compared to 11%. This challenged hypothesis H6 and was in spite of the fact that manufacturing lead-times for the postponed configuration process were considerably shorter than for the keypad assembly process - 3 compared to 17.5 working days respectively. There were two explanations for the unexpectedly low throughput efficiency at the postponed configuration process:

- the size of the generic keypad stock replenishment orders were on average much greater than the size of the customer orders for configured keypads - 520 compared with 45 respectively. The stock replenishment orders were on average equal to one weeks supply and in many cases 2 weeks. This was encouraged by the high generic keypad stock targets - equivalent to 4 weeks cover

- the keypad configuration manufacturing lead-time was extended (by 85% of the lead-time) by queuing caused by capacity restrictions at this process. However, the order lead-times required by the EPP customer were being reliably satisfied. Therefore it appeared that a shorter manufacturing lead-time - or higher throughput efficiency - was not needed.

The above operational features are attributable to flaws in the FPp application at Dewhurst. The high generic stock levels ensure that the stock driven processing is far from the ‘lean’ ideal and the keypad configuration process demonstrates a lack of responsiveness. However greater responsiveness was not required as FPp provided on average double the responsiveness requested on a day to day basis by the customer.

***Production Variety Funnel:*** The number of SKUs at the CODP is more than double the number of finished keypad variants demanded – 179 SKUs compared to 72 finished keypads. This is contrary to the original conceptual model of FPp which predicted the number of SKUs at the CODP to be substantially less than the number of finished items. However locating the CODP at generic keypad and keytip level (rather than at finished keypad level) still provided benefits for Dewhurst - the generic keypads and keytips were more flexible than the finished keypads and certainly of much lower value.

## 6.6 CONCLUSIONS

The FPp application at Dewhurst was not as originally planned but despite this it still provided double the responsiveness required by the customer and the hypotheses were largely unscathed. Originally it was planned that the EPP keypad would be largely supplied in the plastic keytip variant. Only a handful of colour configured keypad variants would be stocked and no components. Further the postponed process would be merely laser marking the legend on the keytips therefore the keypads could be supplied on a very short lead-time.

However, EPP keypad sales were not as the customer (NCR) forecasted – the variety was greater and the steel keytip keypads continued to be in demand. This meant that Dewhurst had to locate the CODP further upstream than planned and stock unconfigured keypads together with many keytip variants. Rather than merely laser marking - gluing and populating of the keytips onto the keypads was also performed to customer order.

Further overestimated EPP keypad sales forecasts lead to excessive generic keypad stocks which ensured that the stock driven generic processing was far from the ‘lean’ ideal and the postponed keypad configuration process demonstrated a lack of responsiveness. This resulted in the findings challenging the throughput efficiency hypothesis.

The product modularity findings fundamentally challenged the hypothesis – these findings were not influenced by flaws in the FPp application. Contrary to predictions product modularity was not related to the inventory management policy.

# CHAPTER SEVEN

# 7 Cross-Case Comparisons

## 7.1 INTRODUCTION

In bringing together the key operational features of the various cases it is helpful to first consider the major elements in common between the cases analysed: Thomas Bolton (TB - Chapter 4), Brook Crompton (BC - Chapter 5) and Dewhurst (Chapter 6). The manufacturing facilities were of a similar size - between 120 and 200 employees and an annual turnover between £13 and £18 million.

In all three cases FPp had been applied some two years prior to the study, in order to improve responsiveness and in each case the FPp application was not ideal. In the BC and Dewhurst cases FPp continued to be applied, but in the TB case FPp had been abandoned by the time the study was conducted. All three studies were retrospective and focussed on a time period of at least 4 months. Each study compared three UoAs – product groups subject to MTO (ETO in the BC case), FPp and MTS.

In the cases of TB and Dewhurst, FPp was applied to products destined for a single customer. In both cases this was their biggest customer accounting for a high proportion of the facility's turnover and, with whom, there was a high degree of mutual dependence.

As discussed above, and later in this chapter, there were a number of highly significant commonalities between the cases in particular all three companies had applied FPp (according the definition used for this research). However there were also many distinctions between the cases. This was a feature of the research design which aims to compare the application of FPp in diverse contexts in order to extend the generalisability of the findings. In order to advance theories in OM it is necessary to seek out both the differences and commonalities between cases. Thus the key distinctions and similarities between the three case studies are presented in this chapter.

This chapter begins by highlighting the diverse nature of the three FPp applications studied in a comparison of contextual considerations including the reasons for the application of FPp. The second section addresses how FPp was applied and the main flaws in its application to provide generaliseable findings. The third section compares the key measures, in relation to the six hypotheses to reveal which, are fundamentally and consistently challenged across the three case studies. The chapter ends with a concluding section.

## 7.2 CONTEXTUAL CONSIDERATIONS

The three products subject to FPp were all industrial products made in medium sized companies in England. They all exhibited ‘component swapping’ modularity (Pine, 1993) where ‘different components are paired with the same basic product’ to provide high variety in the finished product (as discussed in section 2.6.2). All three companies manufactured and stocked the generic or basic product (TB: laid up cable, BC: standard motor, Dewhurst: unconfigured keypad) and then combined them with various differentiating components in the postponed process. These components were sometimes manufactured in-house (Dewhurst keytips and some of BC motor components) or bought-in (many of the BC components and TB polymers).

Apart from these commonalities the three cases of FPp were very different, as the data in Table 7.1 illustrates. The products varied greatly in complexity. The cables made by TB were simple products requiring only 18 distinct components. The keypads made by Dewhurst required 30 distinct components, but the BOM had fewer levels than that for the TB cables. In contrast the motors made at BC were the most complex products studied, requiring on average 160 distinct components and frequently in excess of 200.

***Volume versus variety:*** The EPP keypads manufactured by Dewhurst were mass customised for the High Street banks, as expected in a product subject to FPp. The EPP keypads exhibited high variety at finished product level and high volume at generic product level. In comparison the motors subject to FPp at BC were manufactured in similar variety but very low volumes even at generic product level. The TB cables, though produced in high volumes, exhibited an unexpectedly low level of variety – far below their potential variety. This was in part because the FPp application was artificially restricted to one customer (as discussed in more detail later in this chapter).

**Table 7.1: Cross-case comparison of contextual data relating to the FPp applications**

| | Thomas Bolton (TB) | Brook Crompton (BC) | Dewhurst |
|---|---|---|---|
| ***Product Description*** | Low voltage flexible energy cables | Large Direct Current (LDC) motors | Encrypted Pin Pad (EPP) |
| ***Volume - variety*** | Low variety, high volume | High variety, low volume | High variety, high volume |
| ***Distinct Components*** | 18 | 160 | 30 |
| ***Manufacturing Processes*** | Equipment driven semi-continuous | Labour driven assembly and other processes | Labour driven simple assembly |
| ***Value added processing time for one unit*** | 36 minutes (1km) | 37 hours (1 motor is a typical batch quantity) | 9 minutes |
| ***Reasons for application*** | Improve responsiveness offered by MTO | Improve responsiveness offered by MTO | Improve responsiveness offered by MTO and reduce component inventories |

***Manufacturing Process:*** The manufacturing processes at the three facilities reflected the diversity of the products. Manufacturing at both BC and Dewhurst was labour driven and involved assembly. However at BC a variety of machines were employed in a broad range of processes (including soldering, machining and curing) and organised into process cells. In contrast only simple manual assembly processes requiring a few gluing machines and a lasering machine were conducted at Dewhurst. At TB, manufacturing was semi continuous in that length - rather than discrete parts - was manufactured. Also, cable making was entirely equipment driven and organised as a batch process.

The total value added processing times illustrate the difference between manufacturing a motor and a keypad – 37 hours compared with 9 minutes. A typical batch quantity of cable (60km) required similar value added time to a single motor, however the *manufacturing lead-time* for a motor was typically triple that for a cable. This is evidence of the fragmented nature of motor manufacture, and the lack of work flow resulting from high production variety throughout processing.

***Reasons for applying FPp:*** In all three cases FPp was seen as an alternative to MTO/ETO. MTS was not considered an option for the products subject to FPp. Accordingly FPp was applied to reduce the order lead-time achieved by MTO and thereby to improve responsiveness. In the case of TB there was a need to improve the match between cable supply and their biggest customer's demand, and to avoid the 'feast and famine' supply experienced with MTO. At BC, UK customers expected that motors based on a standard specification would be available on a 3 to 4 week lead-time – not the 10 to 14 week lead-time achieved by ETO.

At Dewhurst the EPP keypad was the only product to be *specifically* designed for "last minute configuration" (FPp). In common with the other cases a reason for applying FPp was to improve the responsiveness of supply to their biggest customer NCR. Vital to Dewhurst was the opportunity to do this without incurring the high component stocks that had plagued the MTO of the previous NCR keypad range.

## 7.3 CHANGE CONTENT & FLAWS IN THE APPLICATIONS

In this section the application of FPp across the three firms is compared with respect to product (and customer) selection, inventory management, manufacturing planning and the main flaws in its application. The highlights are presented in Table 7.2.

***Selection of products and customers:*** In both the TB and the Dewhurst cases FPp was applied exclusively to products for their biggest customers – Volex Powercords (VP) and NCR respectively. FPp provided these customers with an especially high level of responsiveness not afforded to other customers. At TB, the restriction to one customer was artificial – FPp could have been equally well applied to many other cables (withstanding the production scheduling system issues). At Dewhurst the EPP keypad was designed exclusively for NCR, therefore its manufacture using the FPp approach was also exclusive.

At BC the products to be subject to FPp were selected at the generic level (30 UK standard motors) and any motor variants based on these standard specifications were subject to FPp. At Dewhurst only a predefined list of finished EPP keypad items were selected for FPp. Keypads using stocked keytips alone could be offered on a short lead-time because of the long manufacturing lead-time required for the keytips.

**Table 7.2: Cross-case comparison of the 'change content' data for the FPp applications.**

| ***FPp application*** | ***Thomas Bolton (TB)*** | ***Brook Crompton (BC)*** | ***Dewhurst*** |
|---|---|---|---|
| ***Selection of customers and products*** | | | |
| ***Customers*** | VP only | Any | NCR only |
| ***Products*** | High volume finished cables | 30 UK standard motors | All EPP keypads (predefined end items) |
| ***Product and Processes*** | | | |
| ***Stocked generic product*** | 5 Laid-up cables | 30 UK standard motors | 3 Unconfigured keypads |
| ***Postponed processes*** | Sheath extrusion | Modifications | Populating keypad with keytips |
| ***Inventory Management*** | | | |
| ***Standard quoted lead-time*** | 6 – 10 days | 1 – 4 weeks | 1 week |
| ***Customer orders entered onto SOB*** | Every Tuesday | Any time | Daily at 9:00am |
| ***Component supply into the postponed process*** | Supplier consignment stocks | Made in-house, stocked, purchased to order | Made in-house to Kanbans |
| ***Manufacturing Planning*** | | | |
| ***Customer orders*** | Processed by MRP | By-passed MRP | By-passed MRP |
| ***MRP system driven by fixed period MPS used for….*** | All production | MTO, MTS (including generic motors for FPp) | MTS and generic keypads for FPp |
| ***Release manufacturing orders to shopfloor*** | Weekly | Anytime | Daily at 10:30am |
| ***Order Processing and Manufacturing Planning Lead-time*** | 3 days (excluding possible waiting time of 6 days) | 1 - 3 days | 1.5 hours |
| ***Not ideal FPp Applications*** | | | |
| **Flaws in the FPp applications** | Manufacturing planning was not responsive - FPp abandoned after 9 months | Postponed modifications involved removal of parts – sometimes invasive operations. | Not as originally intended – more postponed processes. |

At TB only the cables demanded in high volume at *finished item* level were selected. The result was that for a given generic cable some finished cable variants were subject to FPp whilst others (with only a different sheath colour) were supplied under MTO. The high minimum volume orders required by the polymer supplier lead to this restriction. The sheathing polymer supplied into the postponed process was required on consignment stock to ensure it was available within 24 hours. This was only possible for high volume cables otherwise it was judged that the risk of obsolescence, or the supplier refusing to provide a consignment stock, was too high.

BC and Dewhurst did not have this problem with the supply of components into the postponed process. BC did not provide such a responsive supply to customers and therefore time was available to purchase, or make, many modification components to order. Dewhurst required immediate availability of the keytips for the postponed keypad configuration, however the keytips were made in-house to Kanbans and therefore volume was not a major issue.

***Inventory Management:*** Order promising for BC motors was mainly based on the modification and part availability hence the relatively long and variable quoted lead-time. This was attributable to the high variety of components required, many of which were purchased (or occasionally made at BC) to order. At TB and Dewhurst a standard order lead-time was agreed and - while the required order lead-time did not fall below this - delivery was promised on time, in full. Components and manufacturing capacity was assumed to be available at TB and at Dewhurst. Where the product is truly customised (i.e. the customer's choices are not confined by predefined lists of options but are truly free choices) as at BC, it is probably not possible to give a standardised order lead-time. Instead the lead-time must be determined on the basis of the customisation ordered. However it should still be short compared to the order lead-time required for the complete order driven manufacture of the product.

At BC customer orders were communicated by either hard copy purchase orders or fax depending on the customer. At TB customer orders were communicated by fax every Tuesday. At Dewhurst, customer orders were communicated by EDI every morning at 9:00 am and Dewhurst sales administrators were waiting to process the orders upon transmission. This allowed rapid reliable communication of the orders and included bar code identification for each order so that barcode keypad labels could be printed at Dewhurst. EDI thus appears to be the most efficient way to communicate orders but is only practical when the customer places orders at regular intervals. Further the improved responsiveness offered by EDI transmission of orders can best be realised if orders are processed upon arrival.

***Manufacturing Planning:*** All three facilities employed MRP systems driven by fixed period MPS for manufacturing planning and control. At Dewhurst and BC the MRP systems were relatively responsive – compiled nightly. However at TB the MRP system was only compiled weekly (as it required two full days for compilation). At BC and Dewhurst, released manufacturing orders were downloaded from the MRP systems to the shopfloor nightly and three times daily respectively - compared with the weekly download at TB. However, even though the manufacturing planning systems at BC and Dewhurst were more responsive the customer orders for products subject to FPp completely by-passed the MRP systems.

At TB the lack of responsiveness - inherent in the MRP system - restricted the customer to placing weekly orders every Tuesday. The associated manufacturing orders were subsequently released to the shop-floor every Friday morning. This approach to manufacturing planning for FPp eventually lead to its demise, as discussed later in this section.

At BC, manufacture of the generic motors and ETO motors was planned using the MRP system driven by a one week fixed period MPS. However it had not been possible to set up the MRP system to process the proliferation of postponed modifications due to lack of flexibility in the BOMs. Therefore special instruction sheets were established to control materials for the modifications and the modifications themselves. The acquiring of parts for modifications was cited as a laborious procedure involving manual stock checking and hand written purchase requisitions. Hence from a material control perspective BC would have benefited from the use of an MRP system with configurable BOMs if the time buckets were small - or better still the MRP system was bucketless.

At Dewhurst manufacturing orders subject to MTO were raised by sales, simultaneously released into the factory and downloaded onto the shopfloor three times per day. This ensured a maximum delay of 8 hours between creation of the manufacturing order and availability for manufacture. However this was not considered responsive enough for the EPP keypad orders subject to FPp. Once communicated by EDI to Dewhurst these orders were logged on the manufacturing order system, hard copies printed and manually transferred to the shopfloor – 1.5 hours from order receipt to availability for manufacture. At Dewhurst only stock replenishment orders (including generic keypads for FPp) were planned using a fixed period MPS.

None of the FPp applications studied were ideal. The application at TB was so flawed that it was eventually abandoned. The application at BC incurred unnecessary manufacturing costs, but was still workable and offered benefits compared to MTO. At Dewhurst the FPp application was not as originally intended on the basis of the customer's sales forecast. The flaws in each of the FPp applications, a brief description of the ideal applications and the potential benefits are discussed in greater detail below.

***Flaws in the FPp application at TB:*** TB's manufacturing planning system was too inflexible to support the FPp application without the support of finished cable buffer stocks. There were two major shortfalls in the planning system: a planning time of two days; and a MRP regeneration frequency of once per week. This added a potential six days waiting time before new orders could be processed. In effect the planning lead-time for FPp orders had *not* been reduced at all compared to that for orders subject to MTO. Instead TB's and VP's planning systems were synchronised but this did not take into account VP's high level of deviation from their manufacturing plan.

***Flaws in the FPp application at BC:*** All modifications involved the removal of parts resulting in increased manufacturing costs. In fact almost half the motors modified required invasive modifications involving changes to the magnet body components. This commonly involved a motor strip down which could take up to 3 working days. This suggested that the CODP would be better located further up stream in the manufacturing process. A more suitable location for the CODP would be at the balanced armature stage since the armature was not subject to any modifications.

The magnet body assembly and motor final assembly would be postponed and conducted to customer orders. With a manufacturing lead-time of just 8 working days it would still be possible to provide modified standard motors on a 3 to 4 week lead-time. Though this approach would not reduce the number of generic SKUs it would reduce their value and allow generic stock levels to be increased to improve ex-stock availability without increasing stock value. Further it would naturally take the postponed motor customisation away from the S&R section (which had extremely limited resources and was primarily tasked with service and repairs) and relocated it back in the main LDC manufacturing section. Here the final assembly area, where motor customisation would take place, was shown to have substantial excess capacity.

***Flaws in the FPp application at Dewhurst:*** Originally it was planned that the EPP keypad would be largely supplied in the plastic keytip variant rather than the steel alternative. Further it was envisaged that the number of plastic keytip colour configurations would be limited to a handful, say five, and that only stocks of these keypad variants would be maintained. The principal benefit was that only the laser marking of the legend on the keytips would be performed to specific customer orders. Therefore no component stocks would be required, and the keypads could be supplied on a very short lead-time.

However, the demand for EPP keypads was not as the customer (NCR) forecasted. The steel keytip keypads continued to be demanded in high volumes and the plastic keypad was demanded in eighteen - rather than five - different keytip colour configurations. This meant that Dewhurst had to locate the CODP further upstream than planned and stock the unconfigured keypads together with the many variants of keytips (plastic and steel). The implications of this for processing were that - rather than merely laser marking - gluing and populating of the keytips onto the keypads was also performed to customer order. In addition the overestimated EPP keypad sales forecasts led to excessive unconfigured keypad stocks.

Given the low value adding time (4.5 minutes) to total manufacturing lead-time of the unconfigured keypads it would have been possible for Dewhurst to assemble the keypads entirely to order. This would still require the application of FPp but only the keytips would be manufactured to stock. However by doing this Dewhurst would have lost the buffer stock of unconfigured keypads which protected the generic keypad assembly process from the high demand variability. Consequently the generic keypad assembly process – as well as the gluing and populating process - would have required excess capacity to cope with the high demand variability.

## 7.4 OUTCOME VARIABLES

In this section the units of analysis (UoA) used in each case are compared. Then the six hypotheses are tested against the findings in all three cases to reveal which hypotheses are fundamentally and consistently challenged.

### *7.4.1 Units of Analyses*

Comparing the UoA used in each study a number of distinctions can be made (as summarised in Table 7.3). Firstly, with regard to the scope of the FPp UoAs:

- At TB one cable group, out of the five subject to FPp, was selected for the FPp UoA. This was the group manufactured in the highest volumes, under FPp, and in the factory overall. It was also representative of the other four cable groups subject to FPp in terms of variety and design.

- At BC all LDC motors subject to FPp were selected for the FPp UoA (however only those subject to demand during the study period were studied). This was to ensure that a sufficient number of orders were included in the FPp UoA.

- At Dewhurst all the EPP keypads were subject to FPp and this entire product group was selected for the FPp UoA. In this case the FPp UoA could have been limited to either plastic keytip or steel keytip keypads. However these variants were different with respect to variety, volume and even manufacturing processes therefore it was decided to study both keypad groups.

**Table 7.3: Cross-case comparison of the UoAs used in the case studies**

| *Unit of Analyses* | *Thomas Bolton (TB)* | *Brook Crompton (BC)* | *Dewhurst* |
|---|---|---|---|
| ***ETO/MTO*** | 3183Y1.00 cable | Contract LDC motors | MA Keypads |
| ***FPp*** | 3183Y1.00 cable<br>(1 generic cable) | Modified UK standard LDC motors<br>(24 generic motors) | EPP Keypads<br>(3 generic keypads) |
| ***MTS*** | 3183Y1.00 cable | UK standard LDC motors | PB bodies |
| ***Time Period*** | 5 months | 12 months | 4 months |

Secondly, the three UoA selected for each case are distinct with regard to the similarity of the product groups selected:

- At TB the three UoA were all the same cable group, because any one cable group was manufactured under various inventory management policies – these were dictated by the customer rather than the product group.

- At BC the ETO UoA consisted of different LDC motors to the FPp and MTS UoAs which were both based on the UK standard motor specifications.

- At Dewhurst keypad products were selected for both the FPp and MTO UoA. However, a different product (a pushbutton body) was selected for the MTS UoA because no keypads were MTS.

The net result was that the three UoAs in each case study included products of very similar design. This ensured that the comparison between the different approaches (FPp, MTO and MTS), in terms of the various measures, screened out product-specific factors. The only exception was the MTS UoA in the Dewhurst case - this was not a keypad product like the FPp and MTO UoA. However the complexity of the product and the manufacturing processes were very similar to that for the keypads. The analysis takes this exception into consideration.

### *7.4.2 Demand Profile (H1 and H2)*

The research questions and respective hypotheses relating to the demand profile measures (demand mix, demand variability and volume demand) are:

***What is the demand profile of products selected for manufacture under FPp?***

> **H1: Products are selected for manufacture under FPp rather than MTS when they exhibit high demand mix, high demand variability, and low volume demand at finished product level.**
>
> **H2: Products are selected for manufacture under FPp rather than MTO/ETO when they exhibit high volume demand at generic product level.**

The results from the three case studies are summarised in Table 7.4. Both hypotheses H1 and H2 were tested and supported by all three case studies with the exception of H1 which was challenged by the findings from the TB case study.

***Demand mix, demand variability and volume demand:*** In the TB study both demand mix and demand variability were lower - and volume demand was higher - for cables made under FPp compared with those made under MTS. These unexpected findings were the result of unusual circumstances of this case, rather than being a fundamental challenge to the hypothesis:

- the FPp application (unlike MTS) was artificially restricted to one customer which limited the potential for variations in the product and hence demand mix and demand variability.

- in general cables were only selected for manufacture under FPp when they exhibited volume demand - at *end item level* - high enough to justify a consignment stock of the polymer used in the postponed sheathing process. Again this limited demand mix and increased volume demand at end item level.

**Table 7.4: Cross-case comparison of the demand profile measures related to hypotheses H1 and H2.**

| Hypotheses and Measures | | Thomas Bolton (TB) | | Brook Crompton (BC) | | Dewhurst | |
|---|---|---|---|---|---|---|---|
| | | Tested | Supported | Tested | Supported | Tested | Supported |
| H1: FPp v MTS | Demand mix | Yes | No | Yes | Yes | Yes | Yes |
| | Demand variability | Yes | No | Yes | Yes | Yes | Yes |
| | Volume demand | Yes | No | Yes | Yes | Yes | Yes |
| H2: FPp v MTO | Volume demand (generic level) | Yes | Yes | Yes | Yes | Yes | Yes |

In both the BC and Dewhurst studies, demand mix and demand variability were higher - and volume demand was lower - for products made under FPp compared with those made under MTS. At BC the motors subject to FPp were demanded in four times as many variants as the MTS motors. As a result the demand variability at finished motor level was higher for the FPp motors and volume demand was lower. Similarly at Dewhurst the EPP keypads subject to FPp were demanded in seven times as many variants as the MTS PB bodies. However, here the demand variability at finished product level was only *marginally* higher for the FPp EPP keypads than for the MTS PB bodies. This was because the average number of orders at end item level for both the

EPP keypads and the PB bodies was very similar. In fact half of the ten stocked PB bodies were only subject to one or two orders over the study period and therefore exhibited a very high CV of demand. It is questionable if these PB bodies should have been MTS. If they were excluded from the analysis demand variability dropped significantly.

***Volume demand at generic level:*** As predicted by H2 in all three cases the generic products selected for manufacture under FPp exhibited higher volume demand than those which were MTO. This was attributable to variations in the MTO generic product specification that did not exist in the FPp generic product. In the TB study there were two generic cables in the MTO UoA compared to one in the FPp UoA. In the BC study there were 155 generic motors in the ETO UoA compared to only 24 generic motors in the FPp UoA. Finally in the Dewhurst study there were six generic keypads in the MTO UoA compared to three in the FPp UoA.

### *7.4.3 Customer Service and Demand Amplification (H3 and H4)*

The research questions and respective hypotheses relating to the customer service measures (ex-stock availability, order lead-time and delivery reliability) and the demand amplification measure are:

***What is the impact on customer service of FPp?***

> **H3: FPp considered as an alternative to MTS increases ex-stock availability.**
>
> **H4: FPp considered as an alternative to MTO/ETO reduces order lead-times and increases delivery reliability but introduces demand amplification**

The results from the three case studies are summarised in Table 7.5. Hypothesis H3 was not tested by either the TB or the BC case studies. However it was tested by the Dewhurst study and the findings supported hypothesis H3. Hypothesis H4 was tested and supported by all three case studies with the exception of the delivery reliability findings from the TB study which challenged H4.

***Ex-stock Availability:*** Hypothesis H3 remained untested in the TB study due to a lack of appropriate data. This was also partially true of the BC study. However the principal reason for hypothesis H3 not being tested at BC was that H3 pre-supposed that orders subject to FPp and MTS did *not* pull from the same product stocks as they did at BC.

At Dewhurst the data were unavailable to measure *ex-stock availability* in terms of the proportion of *enquiries and orders* for which the correct stock item was available. Therefore stock records for both the generic EPP keypads (FPp) and the finished PB bodies (MTS) were used to indicate ex-stock availability. For EPP keypads the combination of no stock outs (in the generic keypads), no *enquiries* only firm orders and a high delivery performance (98% on time in full) indicated that ex-stock availability was no less than 98% and most probably 100%. In comparison stock outs were recorded for three of the MTS PB bodies and this alone reduced delivery reliability to 94% on time in full. Unlike the EPP keypads PB bodies were subject to *enquiries* for which the ex-stock availability was not recorded. Therefore it was concluded that ex-stock availability for the PB bodies was at best 94% and therefore lower than for the EPP unconfigured keypads.

**Table 7.5: Cross-case comparison of the customer service and demand amplification measures related to hypotheses H3 and H4.**

| Hypotheses and Measure | | Thomas Bolton (TB) | | Brook Crompton (BC) | | Dewhurst | |
|---|---|---|---|---|---|---|---|
| | | Tested | Supported | Tested | Supported | Tested | Supported |
| H3: FPp v MTS | Ex-stock availability | No | Not tested | No | Not tested | Yes | Yes |
| H4: FPp v MTO | Order lead-time | Yes | Yes | Yes | Yes | Yes | Yes |
| | Delivery Reliability | Yes | No | Yes | Yes | Yes | Yes |
| | Demand Amplification | Yes | Yes | Yes | Yes | Yes | Yes |

At Dewhurst the high ex-stock availability achieved by FPp compared to MTS was attributable to the reduced number of generic product stock keeping units and the accompanying reduction in demand variability.

***Delivery Reliability:*** At TB the delivery reliability achieved by FPp was lower - rather than higher - than that achieved by MTO - only 51% of FPp orders compared to 76% of MTO orders were available OTIF. This challenged hypothesis H4. The reduced delivery reliability under FPp was largely accounted for by 20% of orders that were only partially available on the due date. Two possible explanations were advanced for the poor delivery reliability exhibited by FPp: a lack of postponed sheathing capacity (as suggested by the excess capacity measure in hypothesis H6); and insufficient generic cable stock. The *underlying* cause of these factors was the unusual circumstances of this case. In particular the customer of cables subject to FPp was allowed to call-off finished cables rather than have them delivered upon completion. Therefore finished cable stock existed which provided a buffer against poor delivery reliability such that it was not noticed. Had this not been the case TB would have been forced to address poor delivery reliability and as a result this would no doubt have improved.

In both the BC and Dewhurst studies delivery reliability was higher for products subject to FPp than the MTO products. However at BC the improvement in delivery reliability provided by FPp was unexpectedly modest. There are three possible explanations:

- Often quoted lead-times for the modified motors (FPp) did not take into account availability of modification parts. Also the process of parts acquisition was very laborious and outside the MRP system.

- Extremely limited resources where two thirds of the modifications took place, coupled with the fact that this section was primarily tasked with service and repairs, may have led to the unresponsive execution of modifications (as suggested by the lower delivery reliability measure for this area).

- Low standard motor stocks, providing only 63% ex-stock availability for modified motor orders, may have extended the manufacturing lead-time.

***Order Lead-time:*** In all three case studies the order lead-time achieved by the FPp approach was substantially less than that achieved by MTO, supporting hypothesis H4. As expected this was in part because much of the manufacturing was conducted speculatively to stock rather than to order. However other factors also contributed to the reduction in order lead-time achieved by FPp. At TB the order lead-time achieved by FPp was just under half of the order lead-time achieved by MTO. This was partially due to the synchronisation of the weekly manufacturing planning process at TB's and their customer's factories. At BC the order lead-time achieved by FPp was less than a quarter of that achieved by ETO orders. This was in part due to dramatic reductions in engineering and bought-in parts lead-times. At Dewhurst the order lead-time achieved for the EPP keypads (FPp) was only one fifth of that achieved for the MA keypads (MTO). This was double the responsiveness requested on a day to day basis by the EPP keypad customer and was in part due to a more responsive approach to order processing and manufacturing planning.

***Demand amplification:*** In all three case studies demand amplification was not found for the MTO/ETO UoA but was detected for the FPp application supporting hypothesis H4. As expected demand amplification was always detected in the manufacture of the generic product to stock but not at the postponed manufacture stage. Except for the TB case where demand amplification was detected at the order-driven sheathing process - albeit to a lesser extent. This was attributable to the long weekly planning cycle, which created the opportunity to batch similar customer orders together.

### *7.4.4 Product Modularity and Standardisation (H5)*

The research question and respective hypothesis relating to product modularity and standardisation are:

***What are the product design implications of applying FPp?***

> **H5: Product families subject to FPp will have a higher level of standardisation and modularity than product families subject to MTO/ETO**

The results from the three case studies are summarised in Table 7.6. Hypothesis H5 was fully tested and fundamentally challenged by the product modularity findings from all three studies.

**Table 7.6: Cross-case comparison of the product modularity and standardisation measures related to hypothesis H5.**

| ***Hypotheses and Measure*** | | ***Thomas Bolton (TB)*** | | ***Brook Crompton (BC)*** | | ***Dewhurst*** | |
|---|---|---|---|---|---|---|---|
| | | ***Tested*** | ***Supported*** | ***Tested*** | ***Supported*** | ***Tested*** | ***Supported*** |
| **H5: FPp v MTO** | ***Product standardisation*** | Yes | Yes | Yes | Yes | Yes | Yes |
| | ***Product Modularity*** | Yes | No | Yes | No | Yes | No |

***Product Standardisation:*** In all three case studies products subject to FPp demonstrated a higher level of standardisation than those subject to MTO/ETO. At TB and BC this was both in terms of the proportion of common components and the degree of commonality index. In these two cases the commonality index exhibited by the FPp

UoA was almost three times higher than that for the MTO UoA and it was higher at every level in the BOM. At the lower BOM levels this was due to FPp being applied to fewer generic products than MTO/ETO. At the higher BOM levels, relating to the postponed processes, the high commonality was for different reasons. At TB it was due to the restriction of FPp to one customer which enabled the standardisation of packaging components and limited the range of sheathing compounds. At BC it was simply due to the customers' requirement for less variety in the peripheral components of motors subject to FPp.

At Dewhurst a much greater proportion of EPP keypad components were common to all variants than MA keypad components (48% compared with 3%) and this was due to a single generic body design serving the full range of EPP keypads (with the exception of a single variable component). Unexpectedly the EPP and MA keypads exhibited a very similar degree of commonality index overall - 14% compared with 15% respectively. However the source of commonality was quite different - commonality in the generic keypad was higher for the EPP keypads whereas commonality in the keytips (the configuring components) was higher for the MA keypads.

***Product Modularity:*** In all three cases the degree of modularity exhibited by the products subject to FPp was the same as – rather than higher than - that exhibited by the products subject to MTO/ETO. All the cables manufactured by TB were highly modular. The generic cable, as well as the components supplied to the postponed process, displayed a high degree of modularity. The keypads manufactured by Dewhurst exhibited a lower degree of modularity than the cables due to the lack of modularity in the generic keypad bodies. However the keytips – the only customising component required - were highly modular. The BC motors, the most complex product studied, exhibited the lowest degree of modularity. The major sub-assemblies in the motors exhibited a low degree of modularity, although peripheral components (involved in final assembly) exhibited a high degree of modularity. The majority of the customising components were highly modular and many were peripheral.

The customising components required by all three products subject to FPp were highly modular except for some of the components required for the BC motor modifications. Just under a quarter of the motor modifications required customising components which demonstrated a relatively low degree of modularity and were embedded in major sub-assemblies. The components in the generic products exhibited a lower degree of modularity than the customising components supplied to the postponed process (with the exception of the cables at TB which were highly modular throughout).

The degree of modularity demonstrated by all of the products studied was an incidental characteristic rather than the result of a deliberate product design effort. This was even true of the EPP keypad, which was the only product specifically designed for "last minute configuration" (or FPp).

### *7.4.5 Capacity Utilisation and Throughput Efficiency (H6)*

The research question and the respective hypothesis relating to capacity utilisation and throughput efficiency are:

***What are the manufacturing planning and scheduling implications of applying FPp?***

> **H6: Capability of the postponed transformation process to respond to high demand variability requires excess capacity and high throughput efficiency**

The results from the three case studies are summarised in Table 7.7. Hypothesis H6 was fully tested in the BC and Dewhurst case studies but only tested in part in the TB case, where it was challenged by the excess capacity findings. Hypothesis H6 was fully supported at BC but it was challenged by the throughput efficiency findings in the Dewhurst case study.

**Table 7.7: Cross-case comparison of the excess capacity and throughput efficiency measures related to hypothesis H6.**

| ***Hypotheses and Measure*** | | ***Thomas Bolton (TB)*** | | ***Brook Crompton (BC)*** | | ***Dewhurst*** | |
|---|---|---|---|---|---|---|---|
| | | ***Tested*** | ***Supported*** | ***Tested*** | ***Supported*** | ***Tested*** | ***Supported*** |
| **H6:** | ***Excess capacity*** | Yes | No | Yes | Yes | Yes | Yes |
| | ***Throughput Efficiency*** | No | Not tested | Yes | Yes | Yes | No |

***Excess Capacity:*** In both the BC and Dewhurst cases the excess capacity at the postponed processes (as indicated by low utilisation and high design capacity levels) was higher than at the preceding stock-driven processes supporting hypothesis H6. At BC the final assembly cell (where a third of the postponed motor modifications took place) consistently demonstrated lower utilisation levels than any of the previous cells.

At Dewhurst the average capacity utilisation was significantly lower for the EPP keypad configuration cell than the stock driven EPP assembly cell.

In the TB study the postponed sheathing process consistently exhibited the least excess capacity compared to the preceding processes challenging hypothesis H6. This was attributable to the provision of less capacity at the postponed process which was due to the unusual circumstances at TB. The lack of sheathing capacity contributed to the poor delivery reliability achieved by FPp, which itself challenged hypothesis H4. As previously discussed for hypothesis H4 the existence of finished cable stocks (created by VP's delayed call-offs) provided a buffer against poor delivery reliability. This allowed the low sheathing capacity to persist unaddressed. Had the finished cable buffer stocks not existed TB would have been forced to address poor delivery reliability, and would have probably increased sheathing capacity.

***Throughput Efficiency:*** Hypothesis H6 was not tested with respect to the throughput efficiency measure in the TB case study because it was not possible to take this measure for the postponed process.

In the Dewhurst study the throughput efficiency was higher for the stock driven EPP assembly than it was for the postponed configuration - 27% compared to 11%. This challenged hypothesis H6 and was in spite of the fact that manufacturing lead-times for the postponed configuration process were considerably shorter than for the keypad assembly process - 3 compared to 17.5 working days respectively. There were two explanations for the unexpectedly low throughput efficiency at the postponed configuration process:

- high generic keypad stock targets - equivalent to 4 weeks cover – encouraged large generic keypad stock replenishment orders. These were much greater than the size of the customer orders for configured keypads - 520 compared with 45 respectively. The stock replenishment orders were on average equal to one weeks supply and in many cases 2 weeks.

- queuing caused by capacity restrictions at the postponed configuration process extended the manufacturing lead-time by over 500%. However, the order lead-times required by the EPP customer were being reliably satisfied. Therefore it appeared that a shorter manufacturing lead-time - or higher throughput efficiency - was not needed.

These problems were due to flaws in the FPp application at Dewhurst. The high generic stock levels ensured that the stock driven generic processing was far from the ‘lean’ ideal and the postponed keypad configuration process demonstrated a lack of responsiveness. However greater responsiveness was not required as the FPp application already provided double the responsiveness (on average) requested on a day to day basis by the customer.

The findings from the BC study supported hypothesis H6. The throughput efficiency for the postponed modifications was double that achieved by the stock-driven manufacture of the generic stock motors (21% compared to 10%). However, as in the Dewhurst case, the throughput efficiency measured for the postponed process was highly variable from order to order giving a coefficient of variation of 127% (four times that for generic motor manufacture). The main factor driving the variability in throughput efficiency was the variety of modifications which required anything from 10 minutes to 26 working hours.

In both the Dewhurst and BC case studies the most striking difference between generic product manufacture and the postponed processes was not the throughput efficiencies but the manufacturing lead-times. Postponed processes were clearly more responsive with a manufacturing lead-time equivalent to only 18% of the generic product manufacturing lead-times in both cases.

### *7.4.6 Production Variety Funnel*

At TB and Dewhurst the number of SKUs at the CODP was greater than the number of finished product variants demanded - eight SKUs compared to five finished cables at TB and 179 SKUs compared to 72 finished keypads at Dewhurst. This is contrary to the original conceptual model of FPp which predicted the number of SKUs at the CODP to be substantially less than the number of finished items (see section 2.7).

In both cases this situation was not a feature of the duration of the study but a feature of the product. At TB even if FPp had not been restricted to one customer this situation would have persisted because for every new finished cable variant a new sheathing polymer was likely to be required. At Dewhurst, although the theoretical potential number of finished EPP keypads was much greater than 72, this product was supplied exclusively to one customer and therefore the actual number of finished items was unlikely to change significantly.

At TB and Dewhurst FPp was applied to a set of predefined finished product variants therefore MTS was an option. However, in spite of the increased SKU's required to support FPp (compared to MTS) it still provided benefits - the generic product and component stocks were more flexible than finished product stocks (ensuring lower stock levels) and certainly of much lower value.

The situation was different at BC. Although 24 generic motors were stocked and 51 different components were supplied into the postponed process, the number of SKUs at the CODP was still less than the 56 finished motor variants demanded. This was because many of the components were purchased to customer order which was attributable to two features of the FPp application at BC. Firstly the finished motor specifications were not predefined (as at TB and Dewhurst) instead the motors were truly customised. Therefore to predict and stock the full array of modifying components was impossible. Secondly BC did not need to provide such a responsive supply to their customers (as at TB and Dewhurst) and therefore there was sufficient manufacturing lead-time to purchase (or make) the components to customer order.

## 7.5 CONCLUSIONS

Important commonalities were observed between the three cases of FPp. All involved industrial products exhibiting 'component swapping' modularity (Pine, 1993) where 'different components are paired with the same basic product' to produce high variety in the finished product (as discussed in section 2.6.2).

In all three cases the FPp applications were not ideal and this created anomalies in the findings. The FPp application in the initial study at Thomas Bolton was flawed to the extent that after nine months it could no longer be defined as FPp. At Brook Crompton the FPp application was sustainable, however the customising process involved the removal of previously added components. Finally the FPp application at Dewhurst most closely resembled an 'ideal' application, however it was not the planned ideal application!

The anomalies in the findings (caused by the flaws in the FPp applications) resulted in a number of hypotheses being challenged - not the predicted results but for predictable reasons. The hypotheses were deduced on the basis of an ideal FPp application, therefore some hypotheses were challenged when tested against less than ideal applications. When the complete picture was built up of how FPp was applied in each case study the challenges to the hypotheses were understandable and predictable. Literal replication (Yin, 2003) was sought (as described in section 3.4.3) where results were predicted to be similar for each case. This was not achieved for some hypotheses instead 'theoretical replication' resulted where cases produced contrasting findings but for predictable reasons (Yin, 2003).

In the TB case three hypotheses were challenged (one in its entirety and two in part) as a result of anomalies in the findings. The challenge to the demand profile hypothesis was the result of the FPp application being restricted to one customer and only applicable to high volume *end item* cables (to justify a consignment stock of the sheathing polymer). The challenges to the delivery reliability and excess capacity hypotheses were attributable to the existence of finished cable stocks. These provided a buffer against poor delivery reliability and allowed the lack of postponed process capacity to go unnoticed.

In the BC case no hypotheses were challenged as a result of anomalies in the findings. However in the Dewhurst case the throughput efficiency hypothesis was challenged. High generic stock levels ensured that the stock driven generic processing was far from the 'lean' ideal and the postponed process demonstrated a lack of responsiveness. However greater responsiveness was not required as the FPp application already provided double the responsiveness requested by the customer.

Taking into account the anomalies in the findings the hypotheses remain largely unscathed. Only the product modularity findings *fundamentally* challenged the hypotheses. In all three cases product modularity was not related to the inventory management policy – the products in the three UoA demonstrated very similar levels of modularity.

The elusiveness of an ideal FPp application is evidence of the major operational challenges involved in its application and ensures that FPp as envisaged remains at the conceptual level. The broader implications - revealed by this study - for applying FPp in practice are discussed in the next and final chapter.

# CHAPTER EIGHT

# 8 Conclusions

The purpose of this concluding chapter is to summarise the research project, to describe the contribution to knowledge in the context of the research objectives and to make proposals for further research.

## 8.1 SUMMARY OF THE PROJECT

Postponement is widely recognised as an approach that can lead to superior supply chains, and the application of postponement has been observed as a growing trend in manufacturing and distribution by various surveys and prominent researchers. However, although much is written in the literature on the benefits of postponement, little is still known about its application.

FPp is a phenomenon truly at the 'interface' between logistics and OM employing supply chain and manufacturing systems thinking. The logistics literature considers conditions when FPp is the appropriate strategy. Here FPp tends to be limited to applications where the postponed processes are conducted in the distribution chain and the practical implications of applying FPp are not considered. In terms of the OM literature FPp is a responsive non-MTS approach to mass customisation. However empirical research addressing the needs of non-MTS companies is astonishingly modest and tends not to consider responsive approaches like FPp. FPp is a major enabler to satisfying the more fragmented markets of the future variously described as 'mass customisation'. The literature concerning mass customisation is extensive but much less has been written about its operational implications. Recently a small body of OM literature has emerged that addresses FPp. However it is dominated by mathematical and inventory models which consider delayed product differentiation applied to MTS approaches and therefore is not directly applicable to FPp. With the introduction of a CODP at the generic product stage these models could be very useful in understanding some of the operational implications of FPp.

Thus this research project aims to address how FPp is applied in terms of the operational implications within the manufacturing facility. Here the generic and postponed processes are performed in the same location, normally a factory. The review of logistics, operations and engineering literature related to FPp revealed a number of key operational implications. These concerned product selection, product design, process configuration, inventory management, CODP location, manufacturing planning, demand amplification and customer service. This thinking lead to the development of a theoretical framework, on the basis of an ideal FPp application, from which the following hypotheses were taken:

***What is the demand profile of products selected for manufacture under FPp?***

> **H1: Products are selected for manufacture under FPp rather than MTS when they exhibit high demand mix, high demand variability, and low volume demand at finished product level.**
>
> **H2: Products are selected for manufacture under FPp rather than MTO/ETO when they exhibit high volume demand at generic product level.**

***What is the impact on customer service of FPp?***

> **H3: FPp considered as an alternative to MTS increases ex-stock availability.**
>
> **H4: FPp considered as an alternative to MTO/ETO reduces order lead-times and increases delivery reliability but introduces demand amplification**

***What are the product design implications of applying FPp?***

> **H5: Product families subject to FPp will have a higher level of standardisation and modularity than product families subject to MTO/ETO**

***What are the manufacturing planning and scheduling implications of applying FPp?***

> **H6: Capability of the postponed transformation process to respond to high demand variability requires excess capacity and high throughput efficiency**

Though the hypotheses provide a focus for the study they do not encapsulate it. In addition to the quantitative evidence required to test the hypotheses much qualitative evidence (words rather than numbers) was collected and analysed to address the overriding research question - ‘why and how is FPp applied in manufacturing?’

### *8.1.1 Research Strategy*

Much of the research related to FPp has involved either computer simulation modelling or large sample surveys. Exploring the complex operational issues arising from the application of FPp, requires in-depth case studies of the phenomenon in relation to its real life context. The case-oriented approach seeks to account for all deviating cases, and therefore creates a rich dialogue between theory and evidence (Ragin, 1987). This is particularly significant for this research as the theoretical base is weak. It is said that in an area such as this 'field based approaches are the best ways to find out about the issues, describe the problems, discover solutions and generally ground our theory in the complex, messy world of real organisations' (McCutcheon and Meredith, 1993).

The multiple case study design where each case incorporated multiple units of analysis (UoA) - effectively mini cases within a case - was chosen. The UoAs were based around product groups subject to different inventory management policies – FPp, MTO and MTS. Comparing UoAs within each case enabled the contextual differences between manufacturing facilities (which were not the subject of this study) to be screened out. The cases were selected from the domain of manufacturing facilities in England with the aim of providing diverse contexts in which to study the application of FPp. Diversity was sought in terms of industry and product complexity such that the analytic generalisability of the findings could be extended. The research design was first developed and tested in a pilot study at Thomas Bolton Flexible Cable factory (TB) in Melling where I had worked some 3 years earlier. The two main case studies were conducted at Brook Crompton (BC, electric motor manufacture) and Dewhurst (control systems manufacture). UoAs at TB were from the same cable group, at BC were different LDC motors, and at Dewhurst were EPP keypads, MA keypads and pushbutton bodies.

In all three cases FPp had been applied some two years prior to the study in order to improve customer responsiveness. The operational implications of applying FPp were explored using structured interviews supported by documentary evidence. A set of quantitative variables were compared across the three UoA and the results compared with those predicted by the hypotheses in a strategy called 'pattern matching' (Campbell, 1975).

### *8.1.2 Measuring Form Postponement*

Based on the literature review and the pilot study at TB a number of internal and external variables which measure the outcome of applying FPp were developed. Predictions were made about these variables in the hypotheses therefore the variables were developed to be precise and measurable to enable predictions to be tested against findings. The outcome variables are briefly defined below:

***Demand amplification:*** the amplification of customer demand in the process schedules within a manufacturing facility.

***Ex-stock availability:*** is the proportion of initial customer requests (enquiries or orders) for which the correct product is available ex-stock in sufficient quantities.

***Order lead-time:*** is the time between the customer ordering the product and receiving it.

***Delivery reliability:*** is the ability of the operating facility to meet the agreed terms of delivery with respect to the product type, the quantity ordered and the due date

***Product Modularity (degree of):*** depends on the degree to which the physical product design reflects the functional architecture of the product.

***Product standardisation:*** results in component commonality measured by the proportion of common components in all variants and the degree of commonality index.

***Excess Capacity:*** is the amount that available capacity exceeds demand and manifests itself as 'process idle time' when the process could be producing but the current load does not require this capacity.

***Production Variety Funnel:*** describes in graphical terms the number of physically different items that occur at different stages of the manufacturing process.

***Demand mix:*** number of product items subject to demand.

***Demand variability:*** changes in demand over a given sequence of time buckets measured using the coefficient of variation.

***Volume demand:*** quantity of a given item demanded.

In operationalising the research design some variables were grouped together because they used the same data and were strongly related. Ex-stock availability, order lead-time and delivery reliability were grouped under 'customer service'. The three external demand variables – demand mix, demand variability and volume demand - were grouped under 'demand profile'.

Qualitative evidence was also collected via numerous structured interviews with key personnel. The qualitative evidence included contextual data such as business environment, reasons for applying FPp and product type. But the majority of the qualitative evidence concerned the 'change content' required to apply FPp in a previously MTO and MTS environment. This included product (or customer) selection, inventory management, CODP relocation and manufacturing planning and scheduling. To complete the picture qualitative evidence was collected on problems encountered with the FPp application and potential improvements.

The eleven outcome variables defined were not intended to form a comprehensive description of the FPp application but to focus a broad based measurement of the UoA to identify the differences between FPp, MTO and MTS. The qualitative data corroborated this quantitative evidence (and visa versa), gave explanations for the differences in the outcome variables between the UoAs and provided a description of how in practical terms FPp was applied. This combination of qualitative and quantitative evidence in the case studies helped to triangulate the research findings.

### *8.1.3 Rigour in Case Study Design*

Case studies have traditionally been viewed as a somewhat problematic form of enquiry compared to other empirical methods and the most common concern is lack of rigour in the research design. Yin (2003) proposes four tests to establish the quality of empirical social research. How the research design addresses each test is described below:

> ***Construct validity***: FPp was precisely defined and various indicators and measures were established and tested in the pilot study. In addition both methodological and data triangulation was used to improve construct validity.
>
> ***Internal validity***: the variables were compared between the UoA within each case to screen out contextual differences between manufacturing facilities and show the outcome of applying FPp. The results of the comparison were compared with those predicted in the hypotheses using the pattern matching strategy.

> ***External validity***: case selection relied on *replication* logic rather than *sampling* logic. Here replication means that individual cases can be used for independent corroboration of specific hypotheses as with experiments. In this study the cases were selected to provide variety but each case was expected to support the hypotheses (literal replication). *Analytic generalisation,* where the researcher attempts to generalise a particular set of results to some broader theory was sought rather than statistical generalisation where the findings apply to a population.
>
> ***Reliability***: the quantitative measures and the qualitative interviews were developed and tested in the pilot study. These were documented and repeated in the two main case studies. The same approach to case analysis was used in all cases: pattern matching for the quantitative evidence; and compiling interview transcripts without losing informants identity for the qualitative evidence. Where opinion based evidence was gathered this was validated by the informant.

A second commonly cited weakness of the case study research concerns the population to which the findings can be generalised – external validity - which is dealt with as described above. Consequently case selection in this research sought to extend analytic generalisability by studying FPp in diverse contexts. This was achieved in terms of product complexity, industry and type of customisation as explained in section 8.3 describing the contribution.

## 8.2 CONTRIBUTION TO KNOWLEDGE

This thesis makes a contribution to both logistics and OM knowledge. The contribution to OM is in three areas: non-MTS approaches, mass customisation and postponement.

Amaro et al (1999) points out that 'the literature addressing the needs of companies which produce in response to customers' orders is astonishingly modest'. The needs of the non-MTS sector have been neglected. FPp is distinct from the established non-MTS categories (ATO, MTO and ETO) in a number of ways but particularly in terms of its responsiveness. The research addressing non-MTS approaches tends to consider ATO, MTO and ETO *not* to be responsive - orders are promised on the basis of the availability of components and/or capacity rather than on the basis of a short often standard quoted lead-time as for FPp (for example Hendry and Kingsman, 1989, Yeh, 2000, Segerstedt, 2002).

Mass customisation has been defined as ‘providing numerous customer chosen variations on every order with little lead-time or cost penalty’ (Ahlstrom and Westbrook, 1999). Most of the research on mass customisation is concerned with its strategic impact (for example Gilmore and Pine, 1997, Pine et al, 1993, 1995, Lampel and Mintzberg, 1996, Kotha, 1995, Westbrook and Williamson, 1993). There are few publications concerning the operational implications of mass customisation (for example Pine, 1993, Ahlstrom and Westbrook, 1999, Swaminathan, 2001, MacCarthy et al. 2003).

Recently a small body of OM research has emerged that addresses postponement. A theoretical paper (Yang and Burns, 2003) reviews research on postponement and concludes that still little is known about its application. Most of the OM research on FPp uses variable-oriented models of postponement applications (for example Van Mieghem and Dada, 1999, Aviv and Federgruen, 2001a and 2001b, Ma et al., 2002, Ernst and Kamrad, 2000). Most of these models consider delayed product differentiation applied to MTS approaches and therefore are not directly applicable to FPp.

This thesis contributes to OM knowledge by considering the operational issues of applying FPp. This is a specific and responsive non-MTS approach to mass customisation distinct from existing documented categories, ETO, MTO and ATO. A case study design has been used to address the complexities of applying FPp. This exploratory work could aid the development of variable-oriented models to simulate FPp and its operational implications. On a strategic level this research contributes an inventory management decision framework (shown in Table 8.1) to determine when FPp is a viable alternative to either MTS or MTO on the basis of the product’s demand profile, customer service provided and demand amplification. Also it is concluded that even when a FPp application is flawed as it was in all three case studies it is still worth applying.

Unlike earlier research on mass customisation or postponement this research focuses on the specific operational implications within the manufacturing facility. A second framework is developed (shown in Figure 8.1), which provides practical guidance on how FPp can be applied in terms of product design, inventory management, manufacturing planning and scheduling operations. In addition obstacles to the application of FPp are identified.

This research project contributes to our understanding of the conditions under which FPp is justified and specification of the appropriate FPp strategy (for example Zinn and Bowersox, 1988, Zinn, 1990a, Cooper, 1993, Pagh and Cooper, 1998, van Hoek, 1998a, van Hoek et al. 1998). Previous research considers FPp as an alternative strategy to MTS - not to MTO - and the guidelines are restricted to deciding an appropriate postponement strategy rather than its application. In general only FPp applications where the postponed processes are conducted in the distribution chain have so far been considered. When postponed processes are brought back into the factory it is argued that substantially more complex processes are likely to be capable of postponement, as supported by Van Hoek's, (1998c) survey of companies in Holland.

This research extends logistics knowledge on FPp by considering FPp applications where postponed processes are performed in the same location as the generic processes, normally in a factory (termed 'unicentric' FPp). This tends to involve the postponement of more complex processes than previously considered in logistics research. This research contributes an inventory management decision framework (shown in Table 8.1) which considers when FPp is a viable alternative to either MTS or MTO on the basis of the product's demand profile, customer service provided and demand amplification - all important supply chain issues. Further contributions are made by addressing the complex operational implications (such as process design and manufacturing planning) arising from taking the postponed processes back into the factory. Two main factors contribute to these operational issues. First, increased complexity of the postponed processes and second the requirement that the factory adapt to the FPp strategy. A strategy which incorporates aspects of both MTO and MTS but also has additional specific requirements.

### *8.2.1 Inventory Management Policy Decision Framework*

The inventory management decision framework shown in Table 8.1 shows when FPp is a viable alternative to either MTS or MTO on the basis of the product's demand profile (at generic and end item level), customer service provided and demand amplification.

The framework has various limitations in addition to those already detailed for the whole contribution:

- Considers only 'unicentric' FPp where the postponed processes take place in the same location as the generic processes. Therefore distribution is not considered.
- Demand profile at generic level can be changed either by relocating the CODP or re-designing product and processes as discussed in the section 2.2.3.
- Product value is not considered. If this is particularly high it will tend to discourage stock driven processing and if it is low it will tend to have the opposite effect.

**Table 8.1: Inventory Management Decision Framework for unicentric FPp.**

| ***Decision Determinants*** | | | ***MTO*** | ***FPp*** | ***MTS*** |
|---|---|---|---|---|---|
| ***Product Demand Profile*** | ***End item level*** | *Product mix* | High | High | Low |
| | | *Demand Variability* | High | High | Low |
| | | *Volume demand* | Low | Low | High |
| | ***Generic level*** | *Product mix* | Medium | Low | Low |
| | | *Demand Variability* | Medium | Low | Low |
| | | *Volume demand* | Low | High | High |
| ***Customer Service*** | | *Ex-stock availability* | n/a | High | Medium |
| | | *Order lead-time* | Long | Short | Short |
| | | *Delivery Reliability* | Medium | High | n/a |
| ***Demand amplification*** | | | None | Low | High |

The inventory management decision framework shows the relative values for demand profile, customer service and demand amplification measures for products that appropriate for MTO, FPp and MTS. MTO products should be selected for manufacture using the FPp approach on the basis of demand profile at generic level, required customer service in terms of order lead-time and delivery reliability and implications for demand amplification. Alternatively MTS products should be selected for FPp on the basis of demand profile at end item level and required customer service in terms of ex-stock availability. The criteria for selecting MTO and MTS products for FPp are discussed in more detail below.

MTO products suitable for manufacture under the FPp approach should meet the following criteria:

- Generic product variants which are subject to low demand variability and high volume demand (as in TB and Dewhurst cases). If this is not so then it may be possible to achieve this by standardising the early (or generic) processes, increasing component commonality and reducing the number of generic product variants.

- Products that require high delivery reliability and an order lead-time considerably shorter than that achievable using MTO. A more responsive product supply may be needed to improve competitiveness.

- Component suppliers that can manage levels of demand amplification likely to be introduced by the application of FPp.

MTS products suitable for manufacture under the FPp approach should meet the following criteria

- Products which exhibit high product mix (or *potentially* high product mix), high demand variability and low volume demand at *end item* level. This may be indicated by inaccurate sales forecasting causing large discrepancies between available stock and demand evidenced by stock outs and excessive stocks.

- Products which require high ex-stock availability. Stock outs may be critical and not tolerable by the customer as was the case at Dewhurst.

- Products for which demand amplification is high and causing component supply problems.

- Postponed processes, necessary to apply FPp, must not extend the order lead-time beyond the existing lead-time unless acceptable to the customer.

In conclusion opportunities for applying FPp to MTO products depends on the demand profile at generic level. If this is not appropriate it may be possible to re-design the product through process and component standardisation to create a narrow range of generic products demanded in sufficient volumes for the application of FPp. Opportunities for applying FPp to MTS products depend on the demand profile for the finished products and are indicated by inaccurate sales forecasting, stock outs and excessive stocks. In this case it still may be necessary to re-design the product to establish a narrow range of generic products demanded in sufficient volumes to enable the application of FPp.

### *8.2.2 Practical Implications of Form Postponement*

The main contribution to knowledge of this research project is the practical implications of applying FPp within a manufacturing facility. A framework is developed which provides practical guidance on how FPp can be applied in terms of product design, inventory management, manufacturing planning and scheduling operations.

The original conceptual model of FPp (presented in section 2.7) has been revised and the main conclusions from this research added to it to give the framework shown in Figure 8.1. It applies to 'unicentric FPp' applications (i.e. where the postponed processes take place in the same location as the generic processes) where the product exhibits component swapping modularity. The framework illustrates the major operational implications of applying FPp which are described in this section.

The PVF in the original conceptual model was found not to be suitable for products exhibiting component swapping modularity. In this case the number of SKUs at the CODP could be greater than the number of finished product variants and there still be benefits to be gained from FPp over MTS. The PVF in the framework (Figure 8.1) illustrates that, although the number of *generic products items* at the CODP is always small compared to the number of finished product items, the total number of components supplied into the postponed process may not be. Indeed this was true in all three case studies, and at TB and Dewhurst the total number of SKUs at the CODP was greater than the number of finished product items. In spite of this FPp still provided advantages in inventory management over MTS because the SKUs at the CODP were more flexible – not yet committed to a specific end item.

A final point about the framework – the number of finished product items is not the theoretical potential never to be realised, but the number of finished items that are going to be produced in the foreseeable future. In the case where the product is *not* truly customised (i.e. the customer either selects finished items or optional modules from predefined lists) this is easily calculable so that the PVF demonstrates the SKUs required for a FPp application compared to MTS.

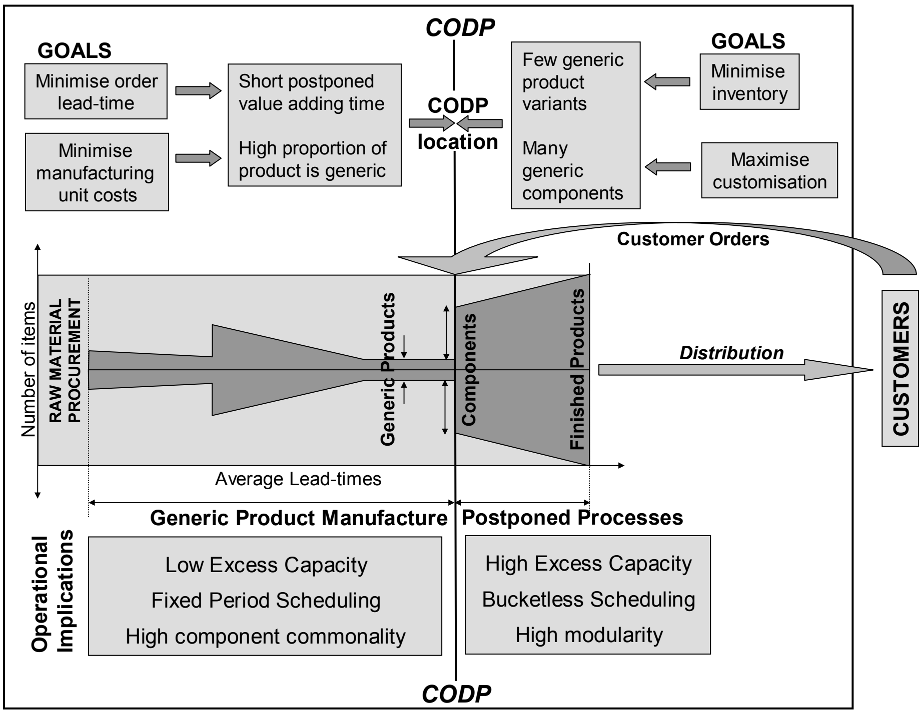



**Figure 8.1: Framework for the application of FPp.**

***Locating the CODP:*** The CODP should be located at a 'neck' in the Production Variety Funnel as illustrated in the framework (Figure 8.1). This is typically at the generic product stage such that:

- no previously added value is removed during the postponed process (as it was at BC) i.e. no removal of components or rework as this adds to the cost of the product

- the postponed value added processing time is short compared to total value adding process time required to manufacture the product to ensure a short order lead-time

- number of generic product variants are kept to a minimum and are each subject to high volume demand and low volume demand variability (CV) relative to the end items.

***Product Design:*** A high proportion of the product should be standardised whilst ensuring that the required customisation levels can still be achieved. Standardisation that involves material redundancy should not be sought (unless absolutely necessary) instead these differentiations should remain and be postponed. The stocked generic products should exhibit a very high level of component commonality. Whilst this is also desirable for any differentiating components supplied into the postponed process, here component commonality must not reduce the achievable customisation level below that required.

Ideally components supplied to the postponed process should be highly modular such that: a one-to-one correspondence exists between each functional element and physical component (or module); and every interaction between components is critical to the function of the system. This enables components to be combined in numerous ways to produce a wide range of product variants.

***Inventory Management:*** Requirements related to order processing and inventory control have been identified:

- EDI is a rapid and reliable way of transmitting customer orders particularly when electronic data such as bar codes are required. However EDI is only practical when the customer places orders at regular intervals. Further the improved responsiveness offered by EDI transmission of orders can best be realised if orders are processed upon arrival. If these conditions do not apply and orders can be placed anytime then some type of broadcasting mechanism must be deployed for the orders upon receipt. This may involve Kanbans been faxed by the customer.

- Generic product stock level should provide forward cover that takes into account volume demand variability (CV) at this level.

- If demand for the generic products and components is stable enough (i.e. demand variability is low enough) generic product and the components can be supplied to the postponed process under Kanban control. This was the case for the keytips at Dewhurst.

- Components into postponed process must be available on a short enough lead-time. In practice this implies that components are available ex-stock. However this is not possible when a product is truly customised since the customising components cannot be predefined (as at BC). In this case it must be ensured that suppliers can deliver to order on a short lead-time. This is often not possible and leads to FPp being limited to a set of predefined end items (as at TB and Dewhurst).

- Generally standard quoted lead-times which apply to all orders are only possible where FPp is applied to a predefined set of end items (as at TB and Dewhurst). Where products are truly customised quoted lead-times must depend on component availability and are difficult to standardise and keep short as the BC case demonstrated.

***Manufacturing Planning and Control:*** A number of requirements related to the manufacturing planning systems and the capacity management are identified:

- The order processing and manufacturing planning systems for the postponed process must be highly responsive. This often requires a real time planning system – a fixed period MRP system for the postponed processing does not support FPp applications for two reasons. Firstly the order processing time from order logging to availability for manufacture tends not to be short enough, in part due to the regeneration frequency of fixed period MRP systems. Secondly fixed period MRP systems restrict due dates to typically weekly time buckets, not appropriate for most FPp applications. Only in the TB case was a fixed period MRP system used for the finished product and the failure of FPp, in this case, was mainly attributable to this. At Dewhurst the existing planning system was by-passed for the FPp application by real time manual planning procedures to provide the required responsiveness. However bucketless MRP systems (described by Vollman et al. 1992) could provide the required responsiveness.

- Where the postponed process is more complex and especially where the product is truly customised (as was the case at BC) an MRP system may be desirable. However configurable BOMs will be required such that any potential finished product BOM can be quickly established for an order. At BC this was not the case, infact it was not possible to configure the BOMs at all. Therefore the existing planning system was by-passed for the FPp application by real time manual planning procedures.

- Substantial excess capacity should be provided at the postponed process to enable it to remain responsive when subjected to high demand variability in terms of product mix and also to a lesser extent volume (i.e. demand variability at generic level). Where sufficient excess capacity is not provided delivery reliability can suffer (as at TB or BC).

- Throughput efficiency is not the crucial issue at the postponed process - it tends to be highly variable. This is largely attributable to variations in value added processing time due to variability in order sizes (as at Dewhurst) or customisations required (as at BC). The crucial aim is to ensure that, even for those orders which involve the highest levels of postponed value added time, the manufacturing lead-time is sufficiently short to satisfy the customer required order lead-times. This may imply limitations to the quantities or customisations that can be delivered within the standard quoted lead-time for FPp.

### *8.2.3 Obstacles to the application of FPp*

***Product design:*** The extent to which it is possible to standardise the product to provide few generic products and modularise the customising components. This is dependant on the demand profile as well as the product characteristics themselves. At Dewhurst the demand profile was such that it was not possible to standardise the colour configured keypad, however by moving the CODP upstream a more standardised generic product was identified. At BC the generic motor was demanded in 24 variants and even moving the CODP upstream would not reduce this number.

***Manufacturing Planning and Control:*** In general the mindsets associated with MTO and MTS present an obstacle to FPp. Both approaches tend not to require either manufacturing planning or manufacturing processes themselves to be responsive.

The existing order processing and manufacturing planning systems are obstacles to the application of FPp as all three cases demonstrate. In both the TB and Dewhurst cases the fixed period MRP systems were found to be insufficiently responsive to process customer orders for FPp products. This manifested itself in two ways: firstly long order processing times, extended in the TB case by infrequent MRP regeneration; secondly time buckets restricting due dates to due weeks rather than days.

In the BC case the MRP system was responsive enough but the BOMs lacked flexibility. It was not possible to configure the BOMs to reflect the modification of a standard motor and this prevented BC from using the MRP system for orders subject to FPp.

***Postponed Process Capacity:*** Postponed process capacity presents an obstacle to the application of FPp when it is insufficient to maintain the required responsiveness in terms of short, reliable lead-times. At TB a lack of excess capacity at the postponed process was a major contributing factor to the reduced delivery reliability provided by FPp compared to MTO. Also at BC the lack of resource and focus in the department performing the postponed modifications was a strong contributing factor to the poor delivery performance.

### *8.2.4 Is Form Postponement worth it?*

The operational requirements and obstacles inherent in the application of 'unicentric FPp' detailed in the previous section represent a major challenge for a manufacturing facility that previously made to order and made to stock. Given the formidable list of changes required the question arises: 'is it worth it?' or would efforts be better invested in improving the existing MTO and MTS approaches.

Each of the three case studies are considered to evaluate this question. At TB the benefits of FPp were never realised because the application was fundamentally flawed.

However, at BC and Dewhurst, though the FPp applications were not ideal, benefits over MTO and MTS were realised but were they worth the effort?

At BC the finished motor specifications subject to FPp were not predefined. Instead the motors were truly customised. Therefore MTS was not an option because it was not possible to predict and stock the full array of finished motors. MTO on the other hand would not have enabled the motors to be delivered within the 3 to 4 weeks lead-time expected by UK customers (for modified standard motors) - the best achievable by MTO was 6 to 10 weeks depending on motor size. In conclusion if Brook Crompton wanted to sell modified standard motors to UK customers the only option was FPp.

At Dewhurst FPp was applied to a set of predefined finished product variants therefore MTS was an option. However this would have required very high finished stock levels to ensure stock availability in the face of such high demand variability. Moreover the customer did not need immediate availability and was satisfied with a 5 working day lead-time. MTO on the other hand was not a possibility because keytip manufacture involved numerous distinct processes, and a high minimum batch quantity, resulting in a long manufacturing lead-time. Applying FPp by making at least the keytips to a speculative stock was the only approach that minimised inventory whilst enabling the customer service need to be met.

At TB if the difficulties with the manufacturing planning and scheduling system had been overcome substantial benefits could have been realised. The design of the majority of TB's cables was ideal for FPp and presented no obstacles. The MTO lead-time of 3 weeks could have been slashed to 3 days enabling cable supply to be matched with the customers demand and all finished stocks eliminated. This would have provided TB with the ability to provide exceptionally responsive service without the need for high value finished goods stock.

The conclusion is that FPp is worth applying where:

- there is a need for greater responsiveness, in terms of shorter order lead-times, than the MTO approach can deliver.

- product variety is such that the stock keeping units required to support a FPp application enable inventory carrying cost reductions - compared to a MTS application - without increasing the order lead-time beyond that required by the customer.

This study reveals that even flawed FPp applications offer significant benefits and are worth applying the question remains ‘is it worth applying FPp in an ideal way?’ Certainly in the BC case improvements in the FPp application would have delivered reduce manufacturing costs and improvements in delivery reliability without reducing responsiveness or increasing inventory costs. However, at Dewhurst, FPp was already providing double the responsiveness requested by the customer and delivery reliability was very high. Therefore there were no advantages to be gained through customer service improvement. Generic product inventory on the other hand was high and this could have been reduced with improvements to the FPp application – either moving the CODP further upstream or reducing the stock levels through increased leanness of the generic processes.

In conclusion improvements in a FPp application are subject to the same criteria as other manufacturing operation improvements – they are only worth implementing if they deliver either reductions in manufacturing costs or improvements in customer service that will provide competitive advantage.

## 8.3 RESEARCH LIMITATIONS

No research design is without its limitations and this research is no exception. Upon reflection of the entire research process three aspects stand out as limiting the findings. These aspects are all related to the chosen case study approach and are discussed below.

### *8.3.1 Case Selection*

Identifying suitable manufacturing facilities for the case studies proved to be extraordinarily difficult and time consuming. Pettigrew (1990) discusses the process of selecting cases:

> *'there is an intentional or design component in the process of choosing and gaining access to research sites, but the practicalities of the process are best characterised by the phrase 'planned opportunism'.*

This is an honest assessment of the approach to case selection for this research which was challenging for many reasons. Not only were the manufacturing facilities required to have applied FPp (according to the working definition), but the research design necessitated that both MTO and MTS approaches must have been applied during the same time period. In addition all three inventory management policies were required to have been applied to products of a similar nature in the manufacture of significant proportions of the facility's production.

Following the pilot study and a failed attempt to identify the remaining cases using anecdotal articles, contacts and the like, a systematic approach was adopted. This involved searching the FAME database of all UK registered companies to identify companies from different industries that could potentially be applying FPp. About 120 introductory letters were sent to previously identified contacts to ascertain which companies were applying FPp and interested in participating in the research. A surprisingly high number of replies were received and many of them claimed to be applying FPp. Unfortunately in many of the cases where FPp was 'found': it was applied to an insignificant proportion of production; MTO nor MTS were applied; it was applied intermittently; or the company was not interested in participating in the study.

Finally after a number of factory visits Brook Crompton, an electric motor manufacturer and Dewhurst, a manufacturer of control systems were found to satisfy all the criteria and agreed to be studied. The three manufacturing facilities selected were not only individually suitable, but also provided the intended diversity in terms of industry, product complexity and even the nature of the manufacturing processes. Therefore, although the process of case selection was somewhat laborious, the case studies were in keeping with the research design.

### *8.3.2 Form Postponement Applications Studied*

In all three cases the FPp applications were not ideal. In practice, or at least during this research, an ideal FPp application could not be found. The FPp application in the initial study at Thomas Bolton was flawed to the extent that after 9 months it could no longer be defined as FPp. At Brook Crompton the FPp application was sustainable, however the customising process involved the removal of previously added components. Finally at Dewhurst an example of FPp was studied which most closely resembled the ideal application, however flaws still remained.

The flaws in the FPp applications created anomalies in the findings which resulted in a number of hypotheses being challenged - not the predicted results but for predictable reasons. The hypotheses were deduced on the basis of an ideal FPp application (in part depicted by the conceptual model of FPp), therefore some hypotheses were challenged when tested against less than ideal applications. When the complete picture was built up of how FPp was applied in each case study the challenges to the hypotheses were understandable and predictable. Literal replication (Yin, 2003) was sought (as described in section 3.4.3) where results were predicted to be similar for each case. This was not achieved for some hypotheses instead ‘theoretical replication’ resulted where cases produced contrasting findings but for predictable reasons (Yin, 2003).

The anomalies in the findings highlighted the effect of various flaws in the FPp applications on the hypotheses. This revealed important links between poor delivery reliability and lack of excess capacity at the postponed process and also suggested that in practice throughput efficiency is not a crucial measure. Taking into account the anomalies in the findings the hypotheses remain largely unscathed except for that regarding product modularity which was fundamentally challenged by each study.

The elusiveness of an ideal FPp application is evidence of the major operational challenges involved in its application and ensures that FPp, as envisaged, remains at the conceptual level. Though limited in its generalisability this project reveals when FPp is the preferred approach as an alternative to MTO or MTS and some of the major operational implications of applying FPp in practice.

### *8.3.3 Data Availability*

A total of twelve variables were measured in each case study and this presented major challenges for data collection. Wherever possible the same type of evidence was used for the measures in each of the three cases however each case presented its own unique challenges and opportunities (as discussed in each case study chapter). In some cases the measure was already taken and data was readily available in the correct form - although this was rare. In most cases the measure had never been taken and raw data had to be compiled and analysed. It was *not* possible to collect the ideal data for *all* the measures in any of the case studies. However there was only one measure where the ideal data was *never* available - the ex-stock availability measure. This measure would have required a special data gathering exercise - not possible in a retrospective study.

Although the retrospective nature of the studies prevented special data gathering exercises it sometimes provided data which would have been unavailable in a real-time study. For example the capacity utilisation data in the TB case study was systematically collected and analysed during the study period but by the time the study was conducted the database had lapsed into disuse.

### *8.3.4 Generalisability of the findings*

FPp was studied in three very different contexts with regard to industry and product complexity. Another distinction that extends the generalisability of the findings is the nature of the postponed 'customisation'. At BC the products were truly customised, that is the customers choices were not confined by pre-defined lists of options but were truly free choices. In the other two cases the products could be more accurately described as 'configured' to order where the customer selected finished products from a pre-defined list of finished items.

The three cases exhibited certain commonalities that limit the generalisability of the findings. The manufacturing facilities were all medium sized (between 120 and 200 employees and an annual turnover between £13 and £18 million) and manufactured industrial products. Previous to applying FPp both MTO and MTS approaches were used. In all three cases the products subject to FPp exhibited 'component swapping' modularity (Pine, 1993) where 'different components are paired with the same basic product' to provide high variety in the finished product (as discussed in section 2.6.2).

## 8.4 FURTHER RESEARCH

The body of knowledge addressing the application of FPp is still small so there are many opportunities for further research. Below four areas for research are identified starting with an expansive survey:

1) ***Survey to assess the extent to which FPp is being applied:*** to identify in which industries FPp is being applied to the greatest extent and why. Which industry sectors appear particularly successful at applying FPp and why. Conversely which sectors are not applying FPp and why – is it not viable or is there a lack of awareness. From my contacts with companies during the case selection exercise I noted a range of attitudes towards FPp. There were companies that had applied FPp successfully in the past but had reduced total manufacturing lead-time to the extent that the MTO approach was now responsive enough. Equally there were those that perceived benefits in the FPp approach and wanted to apply it to their manufacturing in the future but lacked the 'know-how'. The results of a comprehensive survey would contribute to industry specific knowledge on the application of FPp. In addition it could be used to direct further case study work to compare contrasting industry sectors where FPp is being applied very successfully and where it is not.

2) ***Assess the opportunities for FPp provided by outsourcing of module manufacture by ATO companies:*** Many companies who mass customise their products do so by ATO of bought in modules or components as illustrated by NCR (Dewhurst's main customer). This is often the case for consumer products such as PCs e.g. Dell Computer Corporation ATO PCs (Magretta, 1998). Their core processes are therefore, understanding the customers' needs and design of the product – manufacturing just allows the company to keep control of quality and supply. In this situation the bulk of manufacturing is left to the suppliers who take on the challenge of providing a responsive supply of a broad variety of components. The question arises - are these companies applying FPp, as Dewhurst did, to enable them to meet this challenge, and if not why not?

3) ***Assess the opportunities for FPp provided by the internet.*** A number of articles describe how mass customised products are being sold on the Internet. For example McCarthy (2000) describes an internet site where one can obtain customised watches at the same cost as a standard watch sold in retail stores. In contrast to the traditional retailer - which supplies the product immediately ex-stock - purchase from the internet necessitates a lead-time and therefore the opportunity to apply FPp instead of the MTS approach. The question arises - is FPp being applied by companies that manufacture products and sell them on the internet, or are they still supplying from stock or MTO?

4) ***The implications of 'true customisation' for FPp:*** Many companies who claim to mass customise are 'mass configuring' their products. The customer selects either finished products or optional modules from predefined lists and therefore their choice is restricted. This is perfectly acceptable for many products, indeed beneficial for both manufacturer and customer. However for some products this simply is not possible. In the case of BC's LDC motors the modifications required depended on the customer's specific use of the motor and therefore were not predefined. This has many implications for the application of FPp some of which were identified in this research. However further studies are required on responsive manufacturers that are truly customising their products using FPp to fully understand the implications.

# Acronyms used in this Paper

| | |
|---|---|
| AC | Alternating current |
| BC | Brook Crompton, Blackheath site |
| BOM | Bill of Material |
| CV | Coefficient of Variation |
| CODP | Customer Order Decoupling Point |
| DPD | Delayed Product Differentiation |
| DC | Direct Current |
| EDI | Electronic Data Interchange |
| EPP | Encrypted Pin Pad |
| ETO | Engineer-to-order |
| FGS | Finished Goods Stock |
| FPp | Form Postponement |
| ICT | Information and Communication Technology |
| IT | Information Technology |
| LDC | Large direct Current |
| MOB | Manufacturing Order Book |
| MPS | Master Production Schedule |
| MTO | Make-to-order |
| MTS | Make-to-stock |
| OEE | Overall Equipment Effectiveness |
| OM | Operations Management |
| OPD | Order Processing Department |
| OTIF | On Time and In Full |
| PMCS | Production Monitoring and Control System |
| PVF | Production Variety Funnel |
| PB | Push Button |
| SOB | Sales Order Book |
| S&R | Service and Repair Department, Brook Crompton, Blackheath |
| SKU | Stock Keeping Units |
| SCM | Supply Chain Management |
| TB | Thomas Bolton Flexible Cables Ltd., Melling site |
| UoA | Unit of Analysis |
| VP | Volex Powercords, UK |

# References

AHLSTROM, P. and WESTBROOK, R., (1999) Implications of Mass Customisation for Operations Management, *International Journal of Operations and Production Management*, 19, (3).

ALDERSON, W., (1950) Marketing Efficiency and the Principle of Postponement, *Cost and Profit Outlook*, 3, September issue.

AMARO, G., HENDRY, L. and KINGSMAN, B., (1999) Competitive Advantage, customisation and a new taxonomy for Non Make-to-stock Companies, *International Journal of Operations and Production Management*, 19, (4).

ANDEL, T., (1997) Warehousing in Manufacturing: From Inventory Holding to Product Moulding, *Transportation and Distribution*, 38, (9), pp. 80-84.

AVIV, Y. and FEDERGRUEN, A., (2001a) Capacitated Multi-Item Inventory Systems with Random and Seasonally Fluctuating Demands: Implications for Postponement Strategies, *Management Science*, 47, (4), pp. 512-531.

AVIV, Y. and FEDERGRUEN, A., (2001b) Design for Postponement: A comprehensive Characterisation of its Benefits Under Unknown Demand Distributions, *Operations Research*, 49, (4), pp. 578-598.

BAKER, K.R., (1985) Safety Stocks and Component Commonality, *Journal of Operations Management*, 6, (1), pp. 13-22.

BALDWIN, C.Y. and CLARK, K.B., (1997) Managing in an Age of Modularity, *Harvard Business Review*, 75, Sept-Oct, pp. 84-93.

BENNETT, D., and FORRESTER, P, (1994) Product Variety and Just-in-Time: Conflict and Challenge, *The International Journal of Logistics Management*, 5, (1).pp. 73-80.

BERRY, D., (1994) *The Analysis, Modelling and Simulation of a Re-engineered PC Supply Chain*, PhD Thesis, University of Whales, College of Cardiff.

BHATTACHARYA, A.K., JINA, J., and WALTON, A.D., (1995) Turbulence in Manufacturing Systems: its identification and management, *Proceedings of IMC 12 Conference, University College Cork, September 1995*, pp.637-44.

BICHENO, J., (1998) *The Lean Toolbox*, Picsie Books, Buckingham, England.

BLAIKIE, N., (1993) *Approaches to Social Enquiry*, Polity Press.

BOWERSOX, D.J. and CLOSS, D.J., (1996) *Logistical Management: the Integrated Supply Chain Process*, McGraw-Hill.

BUCKLIN, L., (1965) Postponement, Speculation and the Structure of Distribution Channels, *Journal of Marketing Research*, 2, February issue.

BROWN, A.O., LEE, H.L. and PETRAKIAN, R., (2000) Xilinx Improves Its Semiconductor Supply Chain Using Product and Process Postponement, *Interfaces*, 30, (4), pp.65-80.

BROWNE, J., HARHEN, J. and SHIVNAN, J., (1996) *Production Management systems: the Integrated Perspective*, Addison Wesley.

CAMPBELL, D.T., (1975) Degrees of Freedom and the Case Study, *Comparative Political Studie*s, 8, pp. 178-193.

CHIOU, J.S., WU, L.Y. AND HSU, J.C., (2002) The Adoption of Form Postponement Strategy in a Global Logistics System: The Case of Taiwanese Information Technology Industry, *Journal of Business Logistics*, 23, (1), pp.107-124.

CHRISTOPHER, M., (1998) '*Logistics and Supply Chain Management'* 2nd ed. Burr Ridge, IL: Financial Times.

CLOSS, D.J., ROATH, A.S., Goldsby, T.J., ECKERT, J.A., and SWARTZ, S.M., (1998) An Empirical Comparison of Anticipatory and Response-Based Supply Chain Strategies, *The International Journal of Logistics Management*, 9, (2).pp. 21-33.

COLLIER, D.A., (1981) The Measure and Operating Benefits of Component Part Commonality, *Decision Science*, 12, (1).

COLLIER, D.A., (1982) Aggregate Safety Stock Levels and Component Part Commonality, *Management Science*, 28, (11), pp. 1296-1303.

COOPER, J. C., (1993) Logistics Strategies for Global Businesses, *International Journal of Physical Distribution and Logistics Management*, 23, (4).

COUNCIL OF LOGISTICS MANAGEMENT, (1995), *World Class Logistics: the Challenge of Managing Continuous Change*, Oakbrook IL, CLM.

COX, T., (1989) Toward the Measurement of Manufacturing Flexibility, *Production and Inventory Management Journal*, 1st Quarter, pp.68-72.

CRAIG, C.S. and DOUGLAS, S.P., (1996) 'Responding to the Challenges of Global Markets: Change Complexity, Competition and Conscience', *Columbia Journal of World Business*, 31, p.6-18.

DAFT, R.L. and LEWIN, A.Y., (1990) Can Organisation Studies Begin to Break Out of the Normal Science Straitjacket, *Organisation Science*, 1, (1), pp.1-19.

DAPIRAN, P., (1992) Benetton – Global Logistics in Action, *Asia Pacific International Journal of Business Logistics*, 5, (3), pp. 7-11.

DAVIS, S., (1987) *Future Perfect*, Addison-Wesley, Reading, MA.

DAVIS, T. and SASSER, M., (1995), Postponing Product Differentiation, *Mechanical Engineering*, November issue.

DENZIN, N.K., (1978) *The Research Act*, 2nd edition, McGraw-Hill, New York.

DROGE, C., GERMAIN, R. and SPEARS, N.E., (1995) Form Postponement as a Strategic Initiative Affecting Organisational Design, *American Marketing Association*, Summer issue.

EALEY, L., ROBERTSON, D., and SINCLAIR, J., (1996) Beyond supplier tiers: facing the platform strategy, *Motor Business International*, 1st Quarter, pp. 107-120.

EASTERBY-SMITH, M., THORPE, R. and LOWE, A., (1991) *Management Research: An Introduction*, Sage.

EISENHARDT, K.M., (1989) Building Theories From Case Study Research, *Academy of Management Review*, 14 (4), pp 532-550.

EISENHARDT, K.M. (1991) Better Stories and Better Constructs: the Case for Rigour and Comparative Logic, *Academy of Management Review*, 16 (3), pp 620-627.

ELLRAM, L.M., and COOPER, M., (1990) Supply Chain Management, Partnerships, and the Shipper – Third Party Relationship, *The International Journal of Logistics Management*, 1, (2).pp. 1-10.

ELORANTA, E., (1992) The Future Factory: Challenge for one-of-a-kind production, *International Journal of Production Economics*, 28, pp. 131-142.

ERENS, F. and VERHULST, K., (1997) Architectures for Product Families, *Computers in Industry*, 33, pp.165-178.

ERNST, R. and KAMRAD, B., (2000) Evaluation of supply chain structures through modularization and postponement, *European Journal of Operational Research*, 124, (3), pp.495-510.

FEITZINER, E. and LEE, H. L., (1997) Mass Customisation at Hewlett-Packard: the Power of Postponement, *Harvard Business Review*, 75, (1)

FERGUSON, A., (1989) Britain's Best Factories, *Management Today*, November issue.

FISHER, M.L., (1997) What is the Right Supply Chain for Your Product?, *Harvard Business Review*, March-April, pp. 105-116.

FLYNN, B.B., SAKAKIBURA, S., SCHROEDER, R.G., BATES, K.A. and FLYNN, E.J., (1990) Empirical Research Methods in Operations Management, *Journal of Operations Management*, 9 (2), pp. 250-284.

FORRESTER, J.W., (1958) Industrial Dynamics, *Harvard Business Review*, July-August, pp. 37-60.

GARG, A. and TANG, C. S., (1997) On Postponement Strategies for Product Families with Multiple Points of Differentiation, *IIE Transactions*, 29, (8).

GILMORE, J. H. and PINE II, B. J., (1997) The Four Faces of Mass Customisation, *Harvard Business Review*, January – February.

HARLAND, C.M., (1996) Supply Chain Management: Relationships, Chains and Networks, *British Journal of Management*, 7, Special Issue, S63-S80.

HARRISON, A., (1992) *Just-in-Time Manufacturing in Perspective*, Prentice Hall: Hemel Hempstead, UK.

HARRISON, A., (1996) *Investigation of Enablers and Inhibitors to the Flow of Materials in Different Operations Contexts*, PhD Thesis, Cranfield University, School of Management.

HARRISON, A.S., (2002) Case Study Research in D. Partington (ed) *Essential Skills for Management Research*, Sage.

HARRISON, A.S., and VOSS, C.A., (1990) Issues in Setting up JIT Supply, *International Journal of Operations and Production Management*, 10, (2), pp.84-93

HARTLEY, J.F., (1994) Case Studies in Organisational Research in Cassell, C and Symon, G (eds) *Qualitative Methods in Organisational Research: A Practical Guide*, Sage, pp 259-279.

HARVARD BUSINESS SCHOOL, (1985) Benetton (A) Teaching Note.

HE, D.W., and KUSIAK, A., (1996) Performance of Modular Products, *International Journal of Production Research*, 34, (1), pp. 253-272.

HE, D.W., and KUSIAK, A., (1998) Designing an Assembly Line for Modular Products, *Computers and Industrial Engineering*, 34, (1), pp. 37-52

HE, Q.M. and JEWKES, E.M., (2000) Performance Measures of a Make-to-Order Inventory-Production System, *IIE Transactions*, 32, pp. 409-419.

HE, Q.M., JEWKES, E.M. and BUZACOTT, J., (2002) Optimal and Near Optimal Inventory Control Policies for a Make-to-Order Inventory-Production System, *European Journal of Operational Research*, 141, pp. 113-132.

HENDRY, L.C. and KINGSMAN, B.G. (1989) Production Planning Systems and their applicability to make-to-order companies*, European Journal of Operational Research*, 40, (1), pp. 1-15.

HOEKSTRA, S. and ROMME, J., (1992) *Integral Logistics Structures (Developing Customer Oriented Goods Flow),* McGraw Hill: London.

HOULIHAN, J.B., (1985) International Supply Chain Management, *International Journal of Physical Distribution and Materials Management*, 15, (1), pp. 22-38.

HOULIHAN, J.B., (1987) International Supply Chain Management, *International Journal of Physical Distribution and Materials Management*, 17, (2), pp. 51-66.

HOULIHAN, J.B., (1988) International Supply Chains: A New Approach, *Management Decisions*, 26, (3), pp. 13-19.

HUANG, C.C., and KUSIAK, A., (1998) Modularity in Design of Products and Systems, *IEEE Transactions on Systems, Management, and Cybernetics* – Part A: Systems and Humans, 28, (1), pp. 66-77.

HUANG, G.Q., LAN, S.K.L., and MARK, K.L. (2003): The Impacts of sharing Production Information on Supply Chain Dynamics: a Review of the Literature, *International Journal of Production Research*, 41, (7), pp. 1483-1517.

HUSSERL, E., (1946) Phenomenology, in *Encyclopaedia Britannica*, 14th edition, 17, pp. 699-702.

INGER, R. BRAITHWAITE, A., and CHRISTOPHER, M., (1995) Creating a Manufacturing Environment that is in Harmony with the Market – the 'how' of Supply Chain Management, *Production Planning and Control*, 6, (3), pp. 246-257.

JICK, T.D., (1979) Mixing Qualitative and Quantitative Methods: Triangulation in Action, *Administrative Science Quarterly*, 24, pp. 602-611.

JOHANSSON, M., COWLING, P. and MACCARTHY, B., (2000) Synchronous Supply, *Manufacturing Engineer*, February issue, pp.36-40.

JONES, T.C. and RILEY, D.W. (1985) Using Inventory for Competitive Advantage Through Supply Chain Management, *The International Journal of Physical Distribution and Materials Management*, 15, (5), pp. 16-26.

KATAYAMA, H, and BENNETT, D., (1999) Agility, Adaptibility and Leanness: A Comparison of Concepts and a Study of Practice, *International Journal of Production Economics*, 60-61, pp. 43-51.

KEKRE, S. and SRINIVASAN, K., (1990) Broader Product Line: a Necessity to Achieve Success?, *Management Science*, 36, (10).

KIDD, P., (1994) *Agile Manufacturing: Forging New Frontiers*, Addison-Wesley: Wokingham, UK.

KOTHA, S., (1995) Mass Customisation: Implementing the Emerging Paradigm for Competitive Advantage, *Strategic Management Journal*, 16, pp. 21-42.

KRITCHANCHAI, D and MACCARTHY, B., (1999) Responsiveness of the Order Fulfilment Process, *International Journal of Operations and Production Management*, 19, (8), pp. 812-833.

LAMPEL, J. and MINTZBERG, H., (1996) Customizing Customization, *Sloan Management Review*, Fall issue.

LAWLER, E.E., (1985) *Doing Research that is Useful in Theory and Practice in Challenging Traditional Research Assumptions*, Jossey Bass, San Francisco, pp. 1-17.

LEE, H.L., (1996) Effective Inventory and Service Management Through Product and Process Redesign, *Operations Research*, 44, (1), pp. 151-159.

LEE, H. L. and BILLINGTON, C. (1994) Designing Products and Processes for Postponement, in *Management of Design: Engineering and Management Perspectives*, Kluwer Academic Publishers, Boston.

LEE, H. L., BILLINGTON, C. AND CARTER, B., (1993) Hewlett-Packard Gains Control of Inventory and Service through Design for Localisation, *Interfaces*, 23, (4) pp. 1-11.

LEE, H.L., and SASSER, M.M., (1995) Product Universality and Design for Supply Chain Management, *Production Planning and Control*, 6, (3), pp. 270-277.

LEE, H.L., and TANG, C.S., (1997) Modelling the Costs and Benefits of Delayed Product Differentiation, *Management Science*, 43, (1), pp. 40-53.

LEE, H. L., PADMANABHAN, V. and WHANG, S., (1997a) The Bullwhip Effect in Supply Chains, Sloan Management Review, 38, (3), Spring issue, pp.93-102.

LEE, H. L., PADMANABHAN, V. and WHANG, S., (1997b) Information Distortion in a Supply Chain: The Bullwhip Effect, *Management Science*, 43, (4), pp. 546-548.

LING, R.C. and WIDMER, K., (1979) Master Scheduling in a Make-to-Order Plant, *APICS Conference Proceedings*

MA, S, WANG, W AND LIU, L., (2002) Commonality and postponement in multistage assembly systems, *European Journal of Operational Research*, 142, (3), pp.523-538.

MACCARTHY, B., BRABAZON, P.G. and BRAMHAM, J., (2003) Fundamental Modes of Operation for Mass Customisation, *International Journal of Production Economics*, 85, (3), pp. 289-304.

MAGRETTA, J., (1998) The Power of Virtual Integration: An Interview with Dell Computer's Michael Dell, *Harvard Business Review*, March-April.

MAPES, J., (1992) The Effect of Capacity Limitations on Safety Stock, *International Journal of Operations and Production Management*, 13, (10), pp. 26-33..

MARUCHECK, A.S., and McCLELLAND, M.K., (1986) Strategic Issues in Make-to-order Manufacturing, *Production and Inventory Management*, 2nd Qtr.

MASON-JONES, R., and TOWILL, D.R., (1997) Information Enrichment: Designing the Supply Chain for Competitive Advantage, *Supply Chain Management*, 2, (4), pp.137-148.

MASON-JONES, R., NAYLOR, B. and TOWILL, D.R, (2000a) Engineering the Leagile Supply Chain, *International Journal of Agile Supply Chains*, 2, (1), p. 54.

MASON-JONES, R., NAYLOR, B. and TOWILL, D.R, (2000b) Lean, Agile or Leagile? Matching Your Supply Chain to the Marketplace, *International Journal of Production Research*, 38, (17), pp. 4061-4070.

MATSON, J.B. AND MCFARLANE, D.C., (1999) Assessing the Responsiveness of Existing Production Systems', *International Journal of Production and Operations Management*, 19, **(**8), pp. 765-784.

McCARTHY, F.T., (2000) All Yours, *The Economist*, 1st April issue.

McCLAIN, J.O., MAXWELL, W.L., MUCKSTADT, J.A., THOMAS, L.J., and WEISS, E.N., (1984) Comment on 'Aggregate Safety Stock Levels and Component Part Commonality, *Management Science*, 30, (6), pp.772-774.

McCUTCHEON, D.M. and MEREDITH, J.R., (1993) Conducting Case Study Research in Operations Management, *Journal of Operations Management*, 11, pp. 239-256.

MEREDITH, J.R., (1993) Theory Building Through Conceptual Methods, *International Journal of Operations and Production Management*, 13, (5), pp. 3-11.

MEREDITH, J.R., RATURI, A., AMOAKO-GYAMPAH, K and KAPLAN, B., (1989) Alternative Research Paradigms in Operations, *Journal of Operations Management*, 8, (4), pp. 297-326.

METTERS, R.D., (1993) A Method for Achieving Better Customer Service, Lower Costs, and Less Instability in Master Production Schedules, *Production and Inventory Management Journal*, 4th Quarter, pp. 61-65.

MEYER, A., NAKANE, J., MILLER, J.G., and FERDOWS, K., (1989) Flexibility: the Next Competitive Battle the Manufacturing Futures Survey, *Strategic Management Journal*, 10, pp. 135-144.

MINTZBERG, H., (1979) An Emerging Strategy of 'Direct' Research, *Administrative Science Quarterly*, 24, (4) pp. 582-589.

MITROFF, I.T and MASON, R.O., (1982) Business Policy and Metaphysics: Some Philosophical Considerations, *Academy of Management Review*, 7, (3), pp. 361-371.

MORGAN, G. and SMIRCICH, L., (1980) The Case for Qualitative Research, *Academy of Management Review*, 5, pp. 491-500.

MUDA, S. and HENDRY, L., (2002a) Proposing a World-Class Manufacturing Concept for the Make-to-Order Sector, *International Journal of Production Research*, 40, (2), pp. 353-373.

MUDA, S. and HENDRY, L., (2002b) Developing a new World-Class Model for Small and Medium sized Make-to-Order Companies, *International Journal of Production Economics*, 78, pp. 295-310.

NAKAJIMA, S., (1988) *Introduction to Total Productivity Maintenance (TPM)*, Productivity Press, Cambridge, Massachusetts.

NARUS, J.A. and ANDERSON, J.C., (1996) Rethinking Distribution: Adaptive Channels, *Harvard Business Review*, July-August, pp 112-120.

NAYLOR, J.B., NAIM, M.M., BERRY, D., (1999a) Leagility: Integrating the lean and agile manufacturing paradigm in the total supply chain, *International Journal of Production Economics*, 62, (1), pp. 107-118.

NAYLOR, B., MASON-JONES, R., TOWILL, D.R., and CHILDERHOUSE, P., (1999b) Integrating Lean Manufacture and Agile Supply, *Logistics in the Information Age*, $4^{th}$ ISL, Florence, Italy.

NEW, C., (1974) Production Funnels, *Management Decision*, 12, (3), pp. 67-178.

NEW, C., (1977) *Managing the Manufacture of Complex Products*, London, Business Books.

NEW, C., (1993) The Use of Throughput Efficiency as a Key Performance Measure for the New Manufacturing Era, *The International Journal of Logistics Management*, 4, (2), pp. 95-104.

NEW, C., (1996) The Building Blocks of Manufacturing Excellence, *GEC Journal of Research*, 13, (2).

NEW, C., (1998) Mix Flexibility: Breaking the Mould, *Manufacturing Excellence*, issue 4, July.

NEW, C. and SKIPWORTH, H.D., (2000) Understanding Mass Customisation, *Manufacturing and Supply Chain Excellence by Management Today*, issue 6, August

NEW, C. and SZWEJCZEWSKI, M., (1995) Performance Measurement and the Focussed Factory: Empirical Evidence, *International Journal of Operations and Production Management*, 15, (4), pp. 63-79.

NEWMAN, W.R., HANNA, M., and MAFFEI, M.J., (1993) Dealing with the Uncertainties of Manufacturing: Flexibility, Buffers and Integration, *International Journal of Operations and Production Management*, 13, (1), pp. 19-34.

NUNNALY, J., (1978) *Psychometric Theory*, McGraw-Hill, New York.

O'LAUGHLIN, K.A., COOPER, J. and CABOCEL, E., (1993) *Reconfiguring European Logistics Systems*, CLM, Oak Brook II.

OHNO, T, (1988) *Toyota Production System: Beyond Large Scale Production*, Productivity Press, Portland

OLIVER, R.K. and WEBBER, M.D., (1982) 'Supply Chain Management: Logistics Catches up with Strategy, in Christopher, M. (1992) 'Logistics: The Strategic Issues', Chapman and Hall, London, UK, pp63-75.

PAGH, J.D. and COOPER, M.C., (1998) Supply Chain Postponement and Speculation Strategies: How to Choose the Right Strategy, *Journal of Business Logistics*, 19, (2), pp. 13-33.

PATTON, M.Q., (1987) *How to Use Qualitative Methods in Evaluation*, Sage, Newbury Park, CA.

PECK, H., (1998) The Development and Implementation of Co-managed Inventory Agreements in the UK Brewing Industry, *Cranfield School of Management Working Paper Series,* 3/98.

PETTIGREW, A.M., (1990) Longitudinal Field Research on Change: Theory and Practice, *Organisational Science*, 1, (3), August, pp. 267-292.

PETTIGREW, A.M., (1992) The Character and Significance of Strategy Process Research, *Strategic Management Journal*, 13, pp. 5-16.

PINE II, B. J., (1993) *Mass Customisation, the New Frontier in Business Competition,* Harvard Business School Press, Boston.

PINE II, B.J., VICTOR, B. and BOYNTON, A.C., (1993) Making Mass Customisation Work, *Harvard Business Review*, September-October issue.

PINE II, B.J., PEPPERS, D. AND ROGERS, M., (1995) Do You Want to Keep Your Customers Forever?, *Harvard Business Review*, March-April issue.

PLOSSL, G.W., (1985) *Production and Inventory Control Principles and Techniques*, 2nd ed., Prentice-Hall, Englewood Cliffs, NJ.

PROUD, J.F., (1981) Controlling the Master Schedule, *Production and Inventory Management*, 21, (2), pp.78-90.

RAGIN, C.C., (1987) *The Comparative Method*, University of California Press.

SCHONBERGER, R.J., (1982) *Japanese Manufacturing Techniques – Nine Hidden Lessons in Simplicity*, Free Press, New York.

SCHONBERGER, R.J., (1986) *World Class Manufacturing: the Lessons of Simplicity Applied*, Free Press, New York.

SCHONBERGER, R.J., (1996) *World Class Manufacturing: the Next Decade*, Free Press, New York.

SCOTT, C. and WESTBROOK, R., (1991) New Strategic Tools for Supply Chain Management, Physical *Distribution and Logistics Management*, 21, (1), pp. 23-33.

SEGERSTEDT, A., (2002) Production and Inventory Control at ABB Motors and Volvo Wheel Loaders, two examples of MRP in practical use, *Production Planning and Control*, 13, (3), pp. 317-325.

SHAPIRO, R.D., and HESKETT, J.L., (1985) *Logistics Strategy: Cases and Concepts*, West Publishing Company, St Paul, MN.

SHINGO, S., (1981) *Study of Toyota Production System from Industrial Engineering Viewpoint*, Tokyo, Japan Management Association.

SLACK, N., (1987) Manufacturing Systems Flexibility: Ten Empirical Observations, *Management Research Papers, Templeton College*, The Oxford Centre for Management Studies MRP/87/9.

SLACK, N., (1988) Manufacturing Systems Flexibility an assessment procedure, *Computer Integrated Manufacturing Systems*, 1, (1).

SLACK, N., and CORREA, H., (1992), The Flexibilities of Push and Pull, *International Journal of Operations and Production Management*, 12, (4), pp. 82-92.

SLACK, N., CHAMBERS, S., HARLAND, C., HARRISON, A., and JOHNSTON, R., (1998) *Operations Management*, 2nd edition, Financial Times, Pitman Publishing.

SOUTH, J., (1985) Continuous Excess Capacity Versus Intermittent Extra Capacity to Control Average Queue Size in a Random Environment, *Production and Inventory Management Journal*, 1st Qtr, pp103-110.

SOUTH, J.B., and HIXSON, R., (1988) Excess Capacity versus Finished Goods Safety Stock, *Production and Inventory Management Journal*, 3rd Qtr.

STALK, Jr, G., and HOUT, T.M., (1990) *Competing Against Time: How Time-based Competition is Reshaping Global Markets*, New York: The Free Press.

STARBUCK, W., (1995) *Learning from Accidents and Extreme Cases*, keynote address to BAM conference, Sheffield.

STARR, M.K., (1965) Modular Production, a New Concept, *Harvard Business Review*, Nov-Dec, 53, pp. 131-142.

STEELE, D.C. and PAPKE-SHIELDS K.E., (1993) Capacity Slack: Strategic Alternative to Lead-time, *Production and Inventory Management Journal*, 4th Qtr, pp.1-5.

STEVENS, G.C., (1989) Integrating the Supply Chain, *The International Journal of Physical Distribution and Materials Management*, 19, (8)

SUAREZ, F. F., CUSUMANO, M. A., and FINE, C. H., (1996) Empirical Study of Manufacturing Flexibility in Printed Circuit Board Assembly, *Operations Research*, 44, (1).

SWAMIDASS, P.M., (1991) Empirical Science: New Frontier in Operations Management Research, *Academy of Management Review*, 16, (4), pp. 793-814.

SWAMINATHAN, J.M. and TAYUR, S.R., (1998) Managing Broader Product Lines Through Delayed Differentiation using Vanilla Boxes, *Management Science*, 44, (12.2), December special issue, pp. 161-172.

SWAMINATHAN, J.M. and TAYUR, S.R., (1999) Managing Design of Assembly Sequences for Product Lines that Delayed Product Differentiation, *IIE Transactions*, 31, (4), pp.1015-1026.

SWAMINATHAN, J.M., (2001) Enabling Customisation Using Standardised Operations, *Californian Management Review*, 43, (3), pp. 125-135.

SWENSETH, S.R., and BUFFA, F.P., (1991) Implications of Inbound Lead-time Variability for JIT Manufacturing, *International Journal of Operations and Production Management*, 11, (7), pp. 37-48.

TOWILL, D.R. and McCULLEN, P., (1999) The Impact of an Agile Manufacturing Programme on Supply Chain Dynamics, *International Journal of Logistics in Manufacturing*, 10, (1), pp. 83-96.

ULRICH, K.T., (1994) Fundamentals of Product Modularity, in *Management of Design: Engineering and Management Perspectives*, Kluwer Academic Publishers, Boston.

ULRICH, K.T. and SEERING, W.P., (1989) Synthesis of Schematic Descriptions in Mechanical Design, *Research in Engineering Design*, 1, pp. 3-18.

ULRICH, K.T., and TUNG, K., (1991) Fundamentals of Product Modularity, in *Issues in Design/Manufacture Integration*, New York: ASME

UPTON, D.M., (1994) The Management of Manufacturing Flexibility, *Californian Management Review*, 36, (2).

VAN HOEK, R.I., (1998a) *Postponed Manufacturing in European Supply Chains: A Triangular Approach*, University Utrecht.

VAN HOEK, R.I., (1998b) Reconfiguring the Supply Chain to Implement Postponed Manufacturing, *The International Journal of Logistics Management*, 9, (1).

VAN HOEK, R. I., (1998c) Logistics and Virtual Integration: Postponement Outsourcing and the Flow of Information, *International Journal of Physical Distribution and Logistics Management*, 28, (7)

VAN HOEK, R.I., and COMMANDEUR, H.R., (1995) *Het verVAL van de logistiek.* In: Handboek Logistiek, Alphen a.d.Rijn:Samson.

VAN HOEK, R.I., and WEKEN, H.A.M., (1998a) How Modular Production can Contribute to Integration in Inbound and Outbound Logistics, *International Journal of Logistics: Research and Applications*, 1, (1).

VAN HOEK, R.I., and WEKEN, H.A.M., (1998b) The Impact of Modular Production on the Dynamics of Supply Chains, *International Journal of Logistics Management*, 9, (2).

VAN HOEK, R.I., COMMANDEUR, H.R. and VOS, B., (1996) The Impact of Postponement Strategies on Supply Chain Integration, *American Marketing Association*, Summer issue.

VAN HOEK, R.I., COMMANDEUR, H.R. and VOS, B., (1998) Reconfiguring Logistics Systems Through Postponement Strategies, *Journal of Business Logistics*, 19, (1).

VAN HOEK, R.I., (2001) The Rediscovery of Postponement a Literature Review and Directions for Research, *Journal of Operations Management*, 19, pp. 161-184.

VAN MIEGHEM, J.A. and DADA, M., (1999) Price Versus Production Postponement: Capacity and Competition, *Management Science*, 45, (12), pp. 1631-1649.

VAN VEEN, E., (1992) *Modelling Product Structures by Generic Bills of Material*, Elsevier, Amsterdam.

VOLLMAN, T., BERRY, W. and WHYBARK, D., (1992) *Manufacturing Planning and Control Systems*, Irwin, Homewood, IL.

VOSS, C.A., (1995) Operations Management – from Taylor to Toyota – and Beyond?, *British Journal of Management*, 6, December special issue, S17-S29.

VOSS, C., TSIKRIKTSIS, N. AND FROHLICH, M., (2002) 'Case Research in Operations Management', *International Journal of Operations and Production Management*, 22, (2), pp. 195-219.

WALKER, M.A, DABHOLKAR, P.A. and GENTRY, J.J., (2000) Postponement, Product Customisation and Market-oriented Supply Chain Management, *Journal of Business Logistics*, 21, (2), pp. 133- 159.

WEBSTER, S., (2002) Dynamic Pricing and Lead-Time Policies for Make-to-Order Systems, *Decision Sciences*, 33, (4), pp. 579-599.

WEMMERLOV, U., (1984) Assemble-to-Order Manufacturing: Implications for Materials Management, *Journal of Operations Management*, 4, (4), pp. 347-368.

WESTBROOK, R. AND WILLIAMSON, P., (1993) Mass Customisation: Japans New Frontier, *European Management Journal*, 11, (1), pp. 38-45.

WOMACK, J.P., JONES, D.T. and ROOS, D., (1990) *The Machine that Changed the World*, Macmillan International.

YANG, B. and BURNS, N., (2003) Implications of Postponement for the Supply Chain, *International Journal of Production Research*, 41 (9), pp. 2075-2090.

YIN, R.K., (2003) *Case Study Research: Design and Methods*, 3rd edition, Sage, London.

YEH, C.H., (2000) A Customer-focussed Planning Approach to Make-to-Order Production, *Industrial Management and Data Systems*, 100, (4), pp. 180-187.

ZINN, W., (1990a) Developing Heuristics to Estimate the Impact of Postponement on Safety Stock, *The International Journal of Logistics Management*, 1, (2).

ZINN, W., (1990b) Should You Assemble Products Before an Order is Received? *Business Horizons*, 33, (2).

ZINN, W. and BOWERSOX, D. J., (1988) Planning Physical Distribution with the Principle of Postponement, *Journal of Business Logistics*, 9, (2)

# Appendix 1 - Glossary

**Attachment component/module** is an "add on" option module which may or *may not* be selected to build the finished product. Examples include maintenance kit and spare parts (Brown et al., 1996, Hoekstra and Romme, 1992).

**Bill of Material (BOM**) is considered to be an engineering document that specifies the ingredients or subordinate components required to physically make each part number or assembly (Vollman et al, 1992).

**Capacity Planning** is the task of setting the effective capacity of the operation so that it can respond to demands placed on it, and involves deciding how the operation should react to fluctuations in demand. (Slack et al, 1998)

**Capacity utilisation** is the actual output of a process as a proportion of its design capacity (Slack et al, 1998):

$$\text{Capacity Utilisation} = \frac{\text{Actual Output}}{\text{Design Capacity}}$$

where

Actual Output is the actual production achieved measured in either units produced or standard man hours

Design Capacity is the theoretical capacity of an operation not usually achieved in practice. It can be calculated for a production line by multiplying its design speed by the operating time of the plant (Slack et al, 1998). Like actual output it can be measured in units produced or standard man hours.

**Coefficient of variation** (CV) is the ratio of the standard deviation to the average.

**Common component/module** is found in all product variants within the product family or model (Brown et al., 1996).

**Commonality index (degree of)** is the average number of common parent items per distinct component part (Collier, 1981, 1982). Or put another way the average number of incidences of the distinct component parts across the parent items.

$$C = \frac{N}{c}$$

where

N = the sum of immediate parents for all distinct components over a set of end items or product structure levels

c = the total number of distinct components in the set of end items or product structure levels

The higher the degree of commonality index the greater the overall level of component commonality. However, viewing this measure in isolation is not sufficient it must be considered in relation to it's upper bound. The upper bound is when all distinct components are common across all the end items (Collier, 1982) and is therefore equal to the number of end items. Accordingly the commonality index should be interpreted as a percentage of the number of end items in the product group.

**Customer Order Decoupling Point (CODP)** is the point in a value adding process where the product is linked to a specific customer order (Brown et al., 1996, Hoekstra and Romme, 1992, Van Veen, 1992)

**Delivery reliability.** The ability of the operating facility to meet the agreed terms of delivery with respect to the product type, the quantity ordered and the due date (Hoekstra and Romme, 1992). Measured by the On Time In Full(OTIF) measure.

**Demand amplification** was first identified by Forrester (1958) and is the effect where variations in customer demand are amplified with each step upstream in the supply chain, such that the pattern of demand upstream bears little resemblance to the final customer demand (Forrester, 1958). It results in the amplification of orders and inventory fluctuations upstream and is caused by inventory management policies (Huang et al., 2003), demand forecast updating, order batching, price fluctuation and rationing and shortage gaming (Lee et al., 1997). Demand amplification can be illustrated using a mapping approach described by Bicheno (1998) which can be used in two ways: for a single member of a supply chain and for the complete supply chain. The former approach is applicable for this study where the chart shows actual customer orders (demand), manufacturing orders and orders placed on the next stage of manufacture, plotted against time.

**Demand mix** is the number of variants subject to demand.

**Demand uncertainty** is the changes in demand for a given time bucket as it moves in time and approaches the delivery due date (Battacharya et al., 1995) where demand is the forecasted and actual customer order due dates and quantities.

**Demand variability** is the changes in demand over a given sequence of time buckets (Battacharya et al., 1995) where demand is the customer order (or in the case of MTS call-off) due dates and quantities. It can be measured using the coefficient of variation (CV), the ratio of the standard deviation to the average demand.

**Efficiency** is the actual output of a process as a proportion of its effective capacity (Slack et al, 1998)**:**

$$\text{Efficiency} = \frac{\text{Actual Output}}{\text{Effective Capacity}}$$

where

**Actual Output** is the actual production achieved measured in either units produced or standard hours. It is the effective capacity minus the unplanned losses, which are those that are *avoidable* such as absenteeism, breakdowns, rework, and unplanned slow running.

**Effective Capacity** is the design capacity minus the planned losses, which are those that are *unavoidable* such as vacations, maintenance, set-ups, and planned slow running. Planned losses also include planned downtime due to lack of demand, see **excess capacity**.

**Excess Capacity** is the percentage amount that available capacity exceeds *demand*. It can be argued that the manifestation of excess capacity is dependant on whether the process is order-driven (e.g. MTO) or stock-driven (e.g. MTS). In an order-driven situation excess capacity manifests itself as *process idle time*. In a stock-driven situation excess capacity may manifest itself as both process idle time and stock awaiting further processing or despatch because load can be created without demand. Here *process idle time* is the time when the process could be producing but idle because the current load does not require this capacity.

**Ex-stock availability** is the proportion of initial customer requests, whether this is enquiries or orders, for which the correct product is available ex-stock in sufficient quantities. It only applies to MTS and form postponement, not MTO where no product stock is normally kept. For MTS it is measured ex-finished goods stock and for FPp it is measured ex-generic stock.

**Flow Process Charts** document the flow of material through the various processes and also use a number of different symbols to identify the different activities: an operation; a movement of materials from one place to another; an inspection of materials; and a storage or inventory of materials (Slack, 1998)

**Form postponement** is the delay, until customer orders are received, of the final part of the transformation processes, which may be manufacturing processes, assembly processes, configuration processes, packaging, or labelling processes, through which the number of different items proliferates

**Indented BOM** is a list of components from the end item all the way down to the raw materials showing the components of the components and how the product can be built (Vollman et al, 1992)

**Master Production Schedule (MPS)** is a statement of what a company plans to manufacture by quantity and date, for top level items, either finished products or high level configurations of materials (Vollman et al., 1992 and Brown et al., 1996)

**Mix flexibility** is the ability to change the range of products (or product mix) being made by the manufacturing system within a given time period (Slack, 1987)

**Modular BOM** is one of the principal types of planning BOM used where the product structure is of the “X” or hour glass shape. Each module is defined as a single level BOM linking the components to modules, but in this type of BOM neither the components nor modules are linked to the end items. (Vollman et al, 1992)

**On Time In Full measure (OTIF)** = $\frac{\text{on time orders + in full orders}}{\text{total orders evaluated}}$

Where

*On time orders* are those where the actual delivery date was before or on the last committed delivery date.

*In full orders* are those where the actual quantity and type delivered was correct to the order.

**Option component/module** belongs to a group, from which one of the options in the group *must* be selected to assemble or build the finished product (Brown et al., 1996, Hoekstra and Romme, 1992).

**Order lead-time**. The time between the customer ordering the product and receiving it.

**Overall Equipment Effectiveness (OEE)** is a measure of the six big losses of capacity which can be reduced through improved equipment maintenance. The maximisation of OEE is central to the philosophy of Total Productive Maintenance (TPM) (Nakajima, 1988, Bicheno, 1998). OEE is calculated by multiplying three separate factors:

***OEE = availability x performance x quality rate***

Where "availability" measures downtime losses such as machine breakdowns and set-ups; "performance" measures speed losses caused by minor stoppages and slow running; and "quality rate" measures losses through defects such as scrapped production and re-work

$$\textbf{\textit{Availability}} = \frac{\text{Operation Time}}{\text{Total available time when needed}}$$

Where

"Operation time" is "total available time when needed" minus unplanned downtime such as breakdowns, changeovers, time awaiting work or material.

"Total available time when needed" excludes the time when it is planned not to operate for various reasons such as planned maintenance or because no demand is expected

$$\textbf{\textit{Performance}} = \frac{\text{Actual Production}}{\text{Maximum possible production at Design Rate}}$$

Where "design rate" is the maximum rate the equipment was designed to run at for this product specification. Since this rate is rarely achievable even when the equipment is new because of quality issues this rate is often substituted by the *"planned rate"* to give the *Net Performance* measurement and ultimately *Net OEE.*

$$\textbf{\textit{Quality Rate}} = \frac{\text{Good Quality Production}}{\text{Total Actual Production}}$$

**Planning BOM** is any use of Bill of Materials (BOM) approaches for planning purposes only, such as translating the Master Production Schedule (MPS) into subordinate component requirements (Vollman et al, 1992). There are two types of modular BOMs, see modular BOM and super BOM.

**Product family** is a group of products (possibly a particular model) where the different variants are characterised by one or several features. It may be that the products form a coherent set of commercial product versions destined for a particular market segment (Hoekstra and Romme, 1992).

**Product modularity** arises from the physical division of a product into independent components (Ulrich, 1994, Lee, 1996) which can be combined in numerous ways to produce different variations of the product (Starr, 1965, Pine, 1993)

**Product modularity (degree of)** depends on the similarity between the physical and functional architecture of the design and the degree to which the interactions between physical components are critical to the function of the product (Ulrich, 1994). He argues that modularity is a *relative* property – products cannot be classified as either modular or not but rather exhibit more or less modularity in design. A completely modular design embodies a one-to-one correspondence between each functional element and physical component, in which every interaction between components is critical to the function of the system. Here a product can be described functionally by a collection of functional elements linked together by exchanges of signals, material and power. This kind of description is frequently called a schematic description.

**Product standardisation** arises from the design of a product such that the maximum number of constituent components are identical across many (preferably all) of the product variants within a product family. It results in component rationalisation or commonality which can be measured with the **degree of commonality index.**

**Product structure** otherwise known as the BOM structure shows the *distinct* or different components and parts used at each assembly level of the BOM and how they are put together. The 'shape' of the product structure is normally drawn with the vertical axis representing the different levels of assembly where the top is the finished product (Slack et al, 1998, Browne et al, 1996).

**Production variety funnel** is a convenient method for describing in graphical terms the number of physically different items that occur at different stages of the manufacturing process. Typically the vertical axis represents the number of distinct items, the horizontal axis represents the average process lead-time and the process flow is from left to right (New, 1974, 1977)

**Responsiveness** is the ability to respond to fluctuating customer demand in terms of delivery speed or order lead-time. This is an element of responsiveness as defined by MacCarthy's (1998) framework rather than the Matson and McFarlane (1999) definition of production responsiveness as the ability of a production system to achieve its goals in the presence of disturbances.

**Single level BOM** shows only those subordinate components that are immediately required (Vollman et al, 1992). Both the principal planning BOMs (super and modular) are single level BOMS.

**Super BOM** is the most widely used planning BOM. An average end item is defined as a single level BOM showing the average decimal useage of each module (Vollman et al, 1992). The average decimal useage represents the proportion of the total forecast sales for the product family (Brown et al., 1996). This BOM links modules to an average end item, for a product family. The average end item is impossible to build, however sales forecasting is aided by the use of super BOMs. Marketing forecast total sales of the product family and make best estimates on the average decimal usage of the 'options'. The requirements for the modules are calculated by multiplying forecast total sales of the product family by the decimal usage. (Browne et al, 1996).is the most widely used planning BOM.

**Throughput efficiency** is:

$$\frac{\text{work content}}{\text{elapsed time taken}}$$

Where the work content is the time taken for the value adding activities to be performed on a batch quantity, order quantity or single item. Elapsed time taken can be measured from release of the factory order to the despatch, or booking into the warehouse, of the finished order. The elapsed time is the time the factory was available to add value and therefore must be measured over the factory's operating hours (New, 1993). .

**Throughput efficiency at corporate level** is:

$$\frac{\text{“empty plant” process time}}{\text{total days cover}}$$

where "empty plant" process time is the time taken for the value adding activities assuming an average batch size and the total days cover is the raw material, in-process and finished goods stock measured in time to consume (New, 1993).

**Throughput time** is the difference in time between the final due date of a finished item and the date when the first action must be taken. It therefore includes the time taken to obtain the raw materials, produce and deliver the products (Slack et al, 1998).

# Appendix 2 - Interviews

## General Context

**1)** How long have you worked in this role?

**2)** Which company owns this factory and for how long?

**3)** If there has been a recent change in ownership what was the impact of the change?

**4)** Give me a description of the company, how many factories, where located, what products do they produce, and is there any overlap? (check subsids and trading addresses on FAME)

**5)** How long has this factory been in operation?

**6)** What industry does this factory belong to, how is this industry structured and where does this factory fit in?

***Documents: Industry Reports***

**7)** What products are manufactured at this factory? Can you give me a break down of the product groups in terms of volume-variety, value, revenue split, and inventory management policy?

**8)** What is the annual revenue and profit of this factory? (refer to FAME)

***Documents: Company Annual Profit and Loss Sheet***

**9)** How many employees on the site and what proportion is direct labour? (refer to FAME)

**10)** What's the organisation structure and the operating hours?

***Documents: Organisation Chart***

**11)** What are the Key Performance Indicators reported on a regular basis at site level and department level?

***Documents: Performance Reports***

**12)** With respect to ownership, organisation, man management, products, manufacturing processes, manufacturing planning, quality management, plant maintenance, supplier base, customer base: What have been the major changes? What are the current problems and the future plans?

## Market Context

**1)** What markets are the product families supplied to, where are they geographically located and what type are they (final users or industrial)?

**2)** What level of customer service to the markets demand and how close is this company to delivering this?

**3)** Who are the major customers and what's the relationship with them? Development of partnerships, sole suppliers.

**4)** What market share does the factory have?

**5)** Is the market expanding, stable or contracting?

## Identification of UoA and the FPp Application

**1)** What happens to the product after it leaves the factory? Are any further transformations performed on it by the company?

**2)** Describe each of the inventory management policies (MTS, FPp, MTO) used for each of the product groups? When is FGS kept and what are the standard quoted lead-times?

**3)** What determines which inventory management policy is used and consequently how is production split between the different approaches (by product, by customer, by market)?

**4)** What is the **volume demand** (customer order due dates and quantities) for products by inventory management policy, and customer over the past year?

**5)** How **variable is demand** over a year period, is there any pattern is it seasonal?

**6)** For the **FPp** application only:

- the generic stock that is subsequently differentiated to finished product customer order and what demand information drives its production?
- the respective generic processes and postponed processes?
- the promised and actual order lead-times?
- is the manufacture of all products based on the generic product subject to the same inventory management policy?

**7)** When did you start applying FPp and why – what was the driver?

***Opinion***

**8)** Why was FPp applied to some product orders and not to others? Why these customers and these product specifications? ***Opinion***

**9)** What **problems** have you encountered applying FPp?
***Opinion***

**10)** When, how and why has the application of ***FPp*** changed?
***Opinion***

**11)** What other products are you **planning (short and long term)** to apply FPp to, is it in the same way, what's the timing and why these products?

## Inventory Management Process

**1)** Can you describe the order processing procedure for the different inventory management policies from receipt of the customer orders/call-offs to raising factory orders and controlling stock levels. Check list:

***Order Processing:***

**a)** What is the **demand information**, in terms of product breakdown, due date, due quantity and level of commitment provided by the customer (blanket purchase order, individual purchase orders, forward schedules, call offs)?

b) What are the **standard quoted leadtimes** and the approach to order changes?

***Outbound logistics:***

c) What are the **finished stock** agreements and is there any finished stock?

d) How are the **customer deliveries** controlled – products delivered upon completions or called of by the customer

e) Does the customer always receive the delivery the same day it is despatched/shipped from the factory? (need for delivery reliability measure)

f) How is customer invoicing triggered?

***Generic and Finished stock control:***

g) How is the **generic stock** controlled? How are the replenishment factory orders put on the system and what demand information are they based on **(FPp only)?**

h) How is the **finished stock** controlled? How are the replenishment factory orders put on the system and what demand information are they based on **(normally MTS only)?**

i) How are the **factory orders** put on the system and how are the quoted leadtimes determined on these orders **(MTO and FPp only)?**

**2)** For any given inventory management policy does the inventory management process (as described above) vary from customer to customer? If so, the questions above will need to be asked for each customer/UoA combination

**3)** Is there a point in the manufacturing process where production is linked to a specific customer order, i.e. where is the CODP?

## Product Design (Standardisation and Modularity)

**1)** What is Product Engineering's involvement in each customer order?

**2)** From the manufacturing perspective, as opposed to the customer/end application perspective, can the products be split into **product groups** or models and how can the products be further classified?

***Documents: Product Classification***

**3)** What does a **customer specification** normally cover and how does this relate to design?

***Documents: Product Drawing***

**4)** Has there been an effort to **rationalise/standardise the product range** manufactured?

**5)** Are **indented BOM** available for the finished products showing how all the different components are assembled? What format?

**6)** Can you provide me with a **generalised indented BOM** for the product group so I can appreciate the product make-up?

***Documents: Generalised or example indented BOM***

**7)** Is the **product/BOM structure** for the different product groups known, i.e. what documents (possibly BOMs) are available that show all the distinct/different components/modules at each assembly level?

***Documents: BOM Structure***

**8)** How do I identify the common, option and attachment components in the BOM?

**9)** Of all the **common components** have any been deliberately **standardised** for manufacture or put another way would it improve the product design (from a performance or material requirement perspective) if some of the common components were differentiated?

**10)** Why were these components standardised and what were the implications for the customer?

**11)** Is the product **modular** to any degree, i.e. can the product be divided into independent components that can be combined in numerous ways?

**12)** What are the **modules and their functions**? This involves a comparison between the functional architecture of the products and the physical architecture.

***Documents: Functional architecture***

**13)** What is the **unwanted interference** between the modules, i.e. that interference that's not critical to the function of the product?

**14)** At what level in the BOM structure are the **modules**, are they at a single level or on multiple levels?

**15)** How long have these product groups been produced?

**16)** With respect to product design in terms of its modularity, standardisation or variety provided: What have been the major changes? What are the current problems and the future plans?

## Process Design

**1)** Describe the **sequence of manufacturing processes** including the transport, storage and inspection processes starting with the initial raw material delivery?

***Documents: Process routings***

**2)** What are the process routings in terms of works stations and how are these determined: fixed or variable?

**3)** Described how the **product variety** is generated through the processes, what are the variables and their possible values at each process?

***Documents: BOM files***

**4)** What are the average leadtimes for each process which when added together give roughly the expected average throughput time?

**5)** How are the work stations arranged, in groups (work centres) as in a process layout, in cells or product lines?

***Documents: Factory layout***

**6)** How many **work stations** at each process and how are they identified (background for production scheduling)?

***Documents: Work station list***

**7)** To what level are the different processes automated: is the **capacity** equipment or labour driven?

**8)** How does **individual machine capability** differ at each process in terms of which products they are able to process? Are some products only produced on certain machines (background for production scheduling)?

**9)** With respect to the manufacturing process design particularly sequence, layout, capacity/speed and automation: What have been the major changes? What are the current problems and the future plans?

## Manufacturing Planning and Scheduling

**1)** What are the manufacturing planning and control ***systems*** used (OPT, MRP, JIT)?

**2)** Describe the process of ***manufacturing planning*** from orders being present on the SOB to job operations being allocated to work stations (include the duration of each main step)? Does this vary with inventory management policy (i.e. MTO, MTS or FPp)?

**3)** How frequently is a ***manufacturing plan*** generated?

**4)** Describe the process of ***scheduling production*** for each of the processes and controlling job progress through the factory – is push (e.g. using production line schedules) or pull (e.g. Kanbans) scheduling used? Does this vary with inventory management policy (i.e. MTO, MTS or FPp)?

**5)** How can ***demand amplification and throughput efficiency*** be measured? Record of the release dates for factory orders? Record of operation schedules or alternatively finish/output dates for operations on particular factory orders?

**6)** What are the ***allowed lead-times*** for each process used for planning or scheduling purposes and does it depend on the product? (need for Production Variety Funnel and to understand control)

**7)** Which resources are the ***bottlenecks***, how was this determined and how are they treated differently?

**8)** What are the ***batch quantities*** and are Economic / Minimum Order Quantities used?

**9)** How is the ***FPp generic stock level*** controlled? (check for Inventory Management Process Interview)?

**10)** How are the stock levels of ***inbound raw materials*** to the order driven processes controlled (VMI, postponed purchasing, Kanbans)?

**11)** With respect to production scheduling: What have been the major changes? What are the current problems and the future plans ?

## Master Production Schedule

**1)** Is a MPS used in planning production and what production is planned on it?
***Master Production Schedule***

**2)** What is the production unit in the MPS and what are the time buckets?

**3)** How is it generated (manually, by computer) and what are the inputs?

**4)** How frequently is it generated?

**5)** Are planning BOM's used? May be they are used to translate the MPS into subordinate component requirements?
***Planning BOMs***

**6)** To what extent is the MPS sales forecast driven or order driven?

**7)** What is the forecast horizon?

## Capacity Planning (required for Capacity Utilisation measure)

**8)** What is the capacity planning strategy, level capacity plan, chase demand plan or demand management?

**9)** How is capacity planned, is a rough cut capacity plan developed for the MPS?
***Rough Cut Capacity Plan***

**10)** What are the key resources used for the rough cut capacity plan, are these the bottlenecks (Cross check with Manufacturing Scheduling) and how do you know this?

**12)** Is a finite or infinite capacity assumed and if a finite capacity is assumed how is available capacity calculated, are efficiency losses taken into account?

**12)** Are the processes scheduled such that a reserve of excess capacity exists (e.g. available capacity deliberately planned out) if so which ones and how much?

**13)** What's the approach to providing high capacity flexibility (in terms of mix or volume) - short set-ups, multi skilled labour, flexible machinery, committed hours, overtime?

# Customer Service

## Order lead-time

**1)** Are the actual order lead-times (i.e. time between the customer ordering the product and receiving it) measured and if so how?

**2)** What are the planned and actual order lead-times (see Inventory Management Interview for details)?

**3)** What are the reasons for the current order lead-times, and why can't they be shorter?
***Opinion***

**4)** How can I measure the promised and actual order lead-times?

***Data required:*** Date ordered, due/actual delivery dates/quantities

## Delivery Reliability

**5)** Is delivery reliability measured and if so how (On Time In Full, no. of on-time orders, no. of late orders)?

**6)** How would you describe delivery reliability performance and why is it at this level?
***Opinion***

**7)** How can I measure delivery reliability (OTIF)?

***Data required:*** Due/actual delivery dates/quantities, reason for lateness/quantity shortfall.

## Ex-stock availability

**8)** Is ex-stock availability (proportion of initial enquiries for which stock is available - ex- finished stock for MTS and ex- aggregate stock for FPp) measured if so how?

**9)** How would you describe ex-stock availability performance?
***Opinion***

**10)** How can I measure ex-stock availability performance?

***Data required***: Initial enquiry date and delivery date/quantity, quantity of stock available for due date, request accepted as order or refused, reason for refusal

## Capacity Utilisation

**1)** Is capacity utilisation measured for each process if so how? If OEE is used how is availability, performance and quality rate measured? If Capacity Utilisation how is actual output and design capacity calculated and which losses are planned?

**2)** What are the capacity utilisation target levels and how can I access the data?

***Documents: Production Records***

**3)** What are the design, planned and actual production rates? Are these rates different if so why?

**4)** How does the capacity utilisation measure currently account for process idle time, i.e. time when the process could be producing but is idle because the current level of demand does not require this capacity, e.g. planned out time?

**5)** If capacity utilisation is not measured how can I *measure* capacity utilisation (actual output/design capacity) for each process?

***Documents: Production records***

***Data required***: design and planned production rates for each product/process combination, operating times, actual output.

## Throughput Efficiency

**1)** Is **throughput efficiency** measured if so how and what is the target level?

**2)** What are the **value adding activities** the products undergo in the factory (see Process Design Interview)?

**3)** What are the operation ***cycle times***?

**4)** What are the non-**value adding activities** the products undergo in the factory (see Process Design Interview)?

**5)** Do the **inventory levels** of raw material, in-process and finished goods vary according to any particular pattern or cycle?

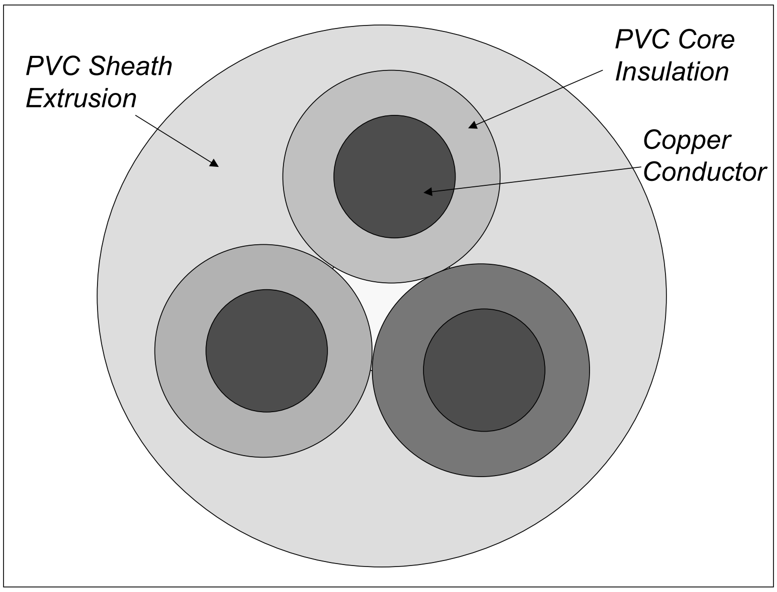
**6)** How can I measure the process **throughput efficiency** for particular orders?

$$\frac{\text{work content}}{\text{elapsed time taken}}$$

***Data required***: Time periods in value added activities and total operating time

# Appendix 3 – TB Change Content Data

**Cross sectional diagram of a 3183Y1.00 cable**

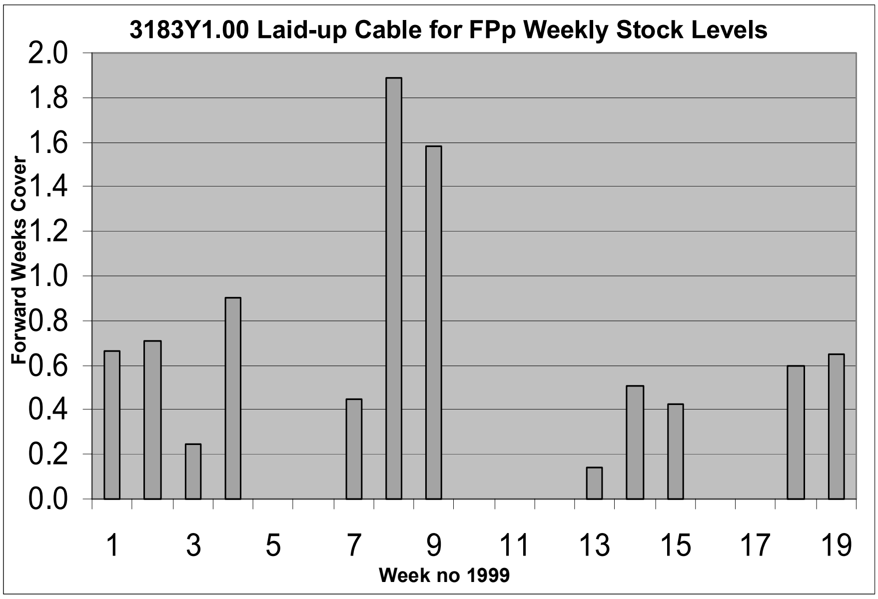



**Inventory Management Notes**

The CODP location for each inventory management policy was clear. For MTO the CODP was at the drawn wire stage, because the wire was drawn to stock whereas the remaining processes were driven by purchase orders. In the case of FPp the factory orders for laid up cable were based on forecasted consumption rates whereas the final sheathing was driven by the Order Schedules, therefore the CODP was at the laid-up cable stage. The CODP for MTS was generally at finished cable since factory orders were based on forecasted sales. However, it was sometimes not quite so clear, for RS Components the factory orders were partially based on actual orders since RS routinely provided 4 week call-off lead-time. The only reason RS cables were made-to-dedicated stock was the orders were below the Minimum Order Quantity (MOQ) and therefore could not be MTO.

The customer dedicated finished cable stocks which were MTS were controlled by the OPD with the aid of an Automatic Stock Replenishment System (ASR). The ASR recommended replenishment orders on the basis of sales forecasts, minimum order quantities and manufacturing lead-times.

## Laid-up Cable Stocks for the FPp Application



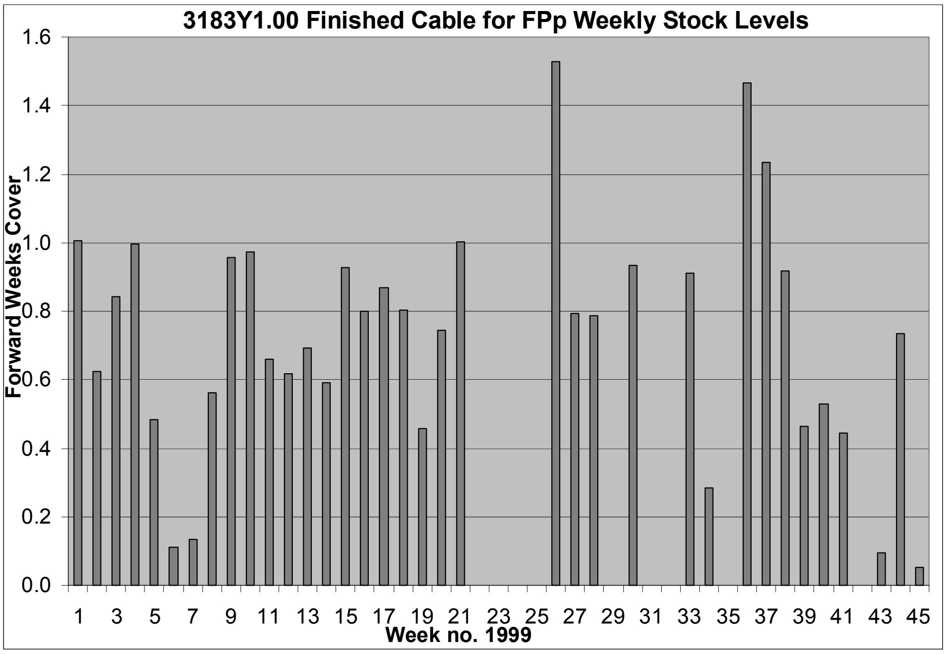

*Notes:*

1) **Where the stock level is zero the data was unavailable**
2) The stock data was sourced from the Scheduling Manager's weekly records of laid-up cable stock which he made every Monday morning
3) The forward weeks cover is calculated using the average demand for 3183Y1.00 cable subject to FPp
4) The average stock level over the study period (weeks 1 to 21) was 0.7 weeks

## Manufacturing Planning and Scheduling System

When the manufacturing jobs were available on PMCS jobs of the same bunch specification were 'batched' together to minimise changeovers on the bunch machines. In fact 8 out of the 13 bunch machines were dedicated to one specification. The same 'batching' process was applied at core extrusion and laying up although it was not possible to batch to the same extent as on bunch because there were fewer machines and a greater number of specifications. After the laying up process the cable destined for the generic cable stock for form postponement was logged into a special stock location and remained there until it was required at sheathing. Naturally 'batching' on the sheath extruders was not as significant as at previous processes because the variety of cables was at its highest.

## Finished Cable Stocks for FPp Application




***Notes:***

1) The stock data was sourced from the OPD's records of finished stock.

2) The study period was weeks 1 to 21. After this period wherever the stock levels are zero the data was unavailable. This is particularly evident between weeks 21 and 26 due to the business system changeover

3) Most of the stock evident in the first 5 weeks was due to stock left over from before FPp

4) The weeks forward cover is calculated by dividing the finished stock level in kilometres by the average weekly demand over the study period weeks 1 to 21.

5) The average weeks cover for 1999 (ignoring the weeks where data was unavailable) was the same as the average weeks cover for the study period at 0.7 weeks.

# Appendix 4 – TB Chronology of FPp Application

**Chronology of changes to the FPp application**

| Date | Event |
|---|---|
| **Nov 1998** | ***FPp was applied*** to 12 of the VP cable products. Originally it was agreed that the cable would be produced on an average 7 day order lead-time, the orders would be called-off in full upon completion, and no schedule changes would be permitted. |
| **Dec 1998** | The ***project champion left*** the FPp application project |
| **4 Jan 1999** | After the first 4 orders the VP Order Schedule was faxed to TB on a Tuesday instead of the Wednesday as originally agreed it seems this was just a matter of routine |
| **March 1999** | ***Finished cable stock*** was still evident. VP were not calling off the cable in full upon completion. |
| **1 June 1999** | ***New business system*** BPCS went live |
| **21 Sept 1999** | The VP Order Schedule changed from requesting next week delivery to next week production and delivery the following. Effectively the ***order lead-time was extended*** from 6-10 days to 13-17 days. |
| **Oct 1999** | ***All VP finished stock was cleared out*** and an agreement for all orders to be called off in full upon completion was made with VP. This was not successful and VP reverted to leaving stock at TB. |

# Appendix 5 – TB Cables in the Units of Analysis

**The 31813Y1.00 finished cables due for delivery between 1 Jan & 31 May 1999.**

| | Product code | Description | Customer |
|---|---|---|---|
| | | **MAKE TO ORDER** | |
| 1 | 20F224248002-DW | Black DW | Doncaster Cables |
| 2 | 20F224248003-DW | White DW | Doncaster Cables |
| 3 | 20F224248009-DW | Orange DW | Doncaster Cables |
| 4 | 20F214333002-19 | Black 1000m | Volex, Asia |
| 5 | 20F214333003-19 | White 1000m | Volex, Asia |
| 6 | 20F214333071-19 | Danish Grey 1000m | Volex, Asia |
| 7 | 20F214333085-19 | OV Grey 1000m | Volex, Asia |
| 8 | 20F224105070-VP | NM PVC Grey Ral 7037 DW | Volex Powercords |
| 9 | 20F224281011-VP | Cream DW | Volex Powercords |
| 10 | 20F224281046-VP | Inter Dark Grey DW | Volex Powercords |
| 11 | 20F224281050-VP | Dove Grey DW | Volex Powercords |
| 12 | 20F224281068-VP | Silver Grey DW | Volex Powercords |
| 13 | 20F224281070-VP | Grey Ral 7037 DW | Volex Powercords |
| 14 | 20F224281077-VP | Grey Ral 7035 DW | Volex Powercords |
| 15 | 20F224281092-VP | Flymo Orange DW | Volex Powercords |
| 16 | 20F224282002-VP | UL2598 PVC Black DW | Volex Powercords |
| | | | Volex ICS, Mexico |
| 17 | 20F224282049-VP | UL2598 PVC Light Grey DW | Volex Powercords |
| 18 | 20F224282069-VP | UL2598 PVC Pebble Grey DW | Volex Powercords |
| | | **FPp** | |
| 1 | 20F224381002-VP | Black DW | Volex Powercords |
| 2 | 20F224381003-VP | White DW | Volex Powercords |
| 3 | 20F224381049-VP | Light Grey DW | Volex Powercords |
| 4 | 20F224381069-VP | Pebble Grey DW | Volex Powercords |
| 5 | 20F224381081-VP | Flint Grey DW | Volex Powercords |
| | | **DEDICATED STOCK** | |
| 1 | 20F224023002-DW | Black DW | Clarke Cable |
| 2 | 20F224723003-DW | SF PVC White DW | Clarke Cable |
| 3 | 20F224023003-DW | White DW | Clarke Cable |
| 4 | 20F224023008-DW | Grey DW | Clarke Cable |
| 5 | 20F224481002-50 | Black DW | Marbourne |
| 6 | 20F224481003-23 | White DW3000m | Marbourne |
| 7 | 20F224481018-50 | Moulinex White DW | Marbourne |
| 8 | 20F224481049-23 | Light Grey DW3000m | Marbourne |
| 9 | 20F224481049-50 | Light Grey DW | Marbourne |
| 10 | 20F224201002-DW | Black SPCL TL DW | Masterplug |
| 11 | 20F224201009-DW | Orange SPCL TL DW | Masterplug |
| 12 | 20F228291004-DW | AG PVC Blue DW | Masterplug |
| 13 | 20F214288002-11 | Black 100m | RS Components |
| 14 | 20F214288003-11 | White 100m | RS Components |
| 15 | 20F214288008-11 | Grey 100m | RS Components |
| 16 | 20F214288009-11 | Orange 100m | RS Components |

# Appendix 6 – TB Cable Sales by Customer

**The 1999 cable sales for Thomas Bolton Flexible Cables, Melling showing the customers included in the UoA shaded.**

| No. | Customer | %age of Total Sales | Inventory Management Policy | Market |
|---|---|---|---|---|
| 1 | Volex Powercords | 22% | MTO or FPp | OEM |
| 2 | Volex, Asia | 10% | MTO | OEM Export |
| 3 | RS Components | 9% | MT dedicated S | Cable Distributor |
| 4 | Masterplug | 6% | MT dedicated S | OEM |
| 5 | UK Cables | 6% | MTO | Cable Distributor |
| 6 | Edmundson Group | 5% | MT free S | Wholesaler |
| 7 | Doncaster | 4% | MTO | Cable Manufacturer |
| 8 | Atco | 3% | MT dedicated S | OEM |
| 9 | Volex ICS, Mexico | 3% | MTO | OEM Export |
| 10 | Wessel | 2% | MTO | Cable Manufacturer |
| 11 | Marbourn | 2% | MT dedicated S | OEM |

# Appendix 7 – TB Demand Measures

**Delivery due date**

At TB the transit time for domestic cable orders was less than 24 hours therefore the delivery due date, as stated on the customer order, was the same as the ex-works due date. However, for the export orders in the MTO UoA the transit times were 4 or 5 weeks. Therefore the ex-works due date was taken as the delivery due date for all orders with the proviso that for export there was a transit time

**Estimation of Ex-works Due Date for Unavailable MTO Customer Orders**

21 out of a total of 79 customer order documents were missing for the MTO UoA. However, the factory order due dates into despatch were known from PMCS and an analysis of the existing customer orders revealed that generally this date is the Saturday before the ex-works due week. Therefore it was possible to estimate the ex-works due date for the missing orders. A total of 80 orders in the MTO UoA were due for despatch between 1 January and 31 May 1999. The customer order document giving the customer due delivery date (and the order date) could not be found for 21 of the orders (all 12 Volex ICS, 2 Volex Asia, 2 Volex Powercords and 5 Doncaster). For all orders the factory order due date into despatch was known and generally this date is the Saturday before the ex-works due week. This is supported by the 59 customer orders that are available 42 had been given a factory order due date which was the Saturday before the week it was due. The remaining 17 were all Volex Asia orders of which there was a total of 26. The factory order due date was generally 1 or 2 weeks before the customer ex-works due week (8 orders had a PMCS due date 2 weeks before, 5 orders 1 week before, 9 orders the Saturday before and 4 orders had a PMCS due date the Saturday at the end of the week due). On average for Volex Asia orders the factory order due date was either the Saturday before it was due to be despatched or 1 week before. From the interview with the respective customer service assistant it is most probable that the ex-works due dates for the other export customer Volex ICS will have a similar relationship with the factory order due dates. Therefore for the 21 missing customer orders the due ex-works date is assumed to be the week after the factory order due date. Of course in reality for all 14 missing export orders the ex-works due date may have been 1 or 2 weeks later.

## Demand measures for FPp UoA

| Item no. | Cable Description | Weekly Demand | | | Totals | |
|---|---|---|---|---|---|---|
| | | Avg. | SD | CV (%) | Demand (km) | Weekly Orders |
| 20F224381002-VP | Black DW | 113 | 149 | **132** | **2380** | 12 |
| 20F224381003-VP | Flint Grey DW | 46 | 69 | **151** | **960** | 11 |
| 20F224381049-VP | Light Grey DW | 44 | 69 | **157** | **930** | 8 |
| 20F224381069-VP | Pebble Grey DW | 21 | 39 | **187** | **435** | 7 |
| 20F224381081-VP | White DW | 5 | 11 | **219** | **105** | 4 |
| **Total** | **5 end items** | **229** | **159** | **70** | **4810** | **42** |
| **Average per end item** | | **46** | | **169** | **962** | **8** |

## Demand measures for MTO UoA

| Cable Description | Customer | Weekly Demand | | | Totals | |
|---|---|---|---|---|---|---|
| | | Avg. | SD | CV (%) | Demand (km) | Orders |
| Black DW | Doncaster | 8 | 21 | 255 | 170 | 3 |
| White DW | Doncaster | 31 | 75 | 237 | 660 | 5 |
| Orange DW | Doncaster | 1 | 4 | 458 | 20 | 1 |
| Black 1000m | Volex Asia | 133 | 124 | 93 | 2786 | 23 |
| White 1000m | Volex Asia | 1 | 4 | 458 | 20 | 1 |
| Danish Grey 1000m | Volex Asia | 3 | 7 | 251 | 60 | 3 |
| OV Grey 1000m | Volex Asia | 1 | 4 | 458 | 20 | 1 |
| NM PVC Grey Ral | **Volex P'cords** | 1 | 3 | 458 | 15 | 1 |
| Cream DW | **Volex P'cords** | 1 | 4 | 458 | 20 | 1 |
| Inter Dark Grey DW | **Volex P'cords** | 6 | 14 | 216 | 135 | 5 |
| Dove Grey DW | **Volex P'cords** | 8 | 18 | 223 | 165 | 4 |
| Silver Grey DW | **Volex P'cords** | 5 | 14 | 290 | 105 | 3 |
| Grey Ral 7037 DW | **Volex P'cords** | 1 | 3 | 458 | 15 | 1 |
| Grey Ral 7035 DW | **Volex P'cords** | 1 | 3 | 458 | 15 | 1 |
| Flymo Orange DW | **Volex P'cords** | 3 | 7 | 281 | 55 | 3 |
| **Sub-total** | **15 end items** | **203** | **136** | **67** | **4261** | **56** |
| UL2598 PVC Black | **Volex P'cords** /ICS Mexico | 33 | 46 | 138 | 195<br>535 | 6<br>12 |
| UL2598 PVC Lgt Gy | **Volex P'cords** | 6 | 12 | 189 | 135 | 5 |
| UL2598 PVC Pb Gy | **Volex P'cords** | 2 | 11 | 458 | 50 | 1 |
| **Sub-total** | **3 end items** | **42** | **45** | **107** | **885** | **23** |
| **Total** | **18 end items** | **245** | **147** | **60** | **5146** | **79** |
| **Average per end item** | | **14** | | **324** | **286** | **4** |

**Demand measures for MTS UoA**

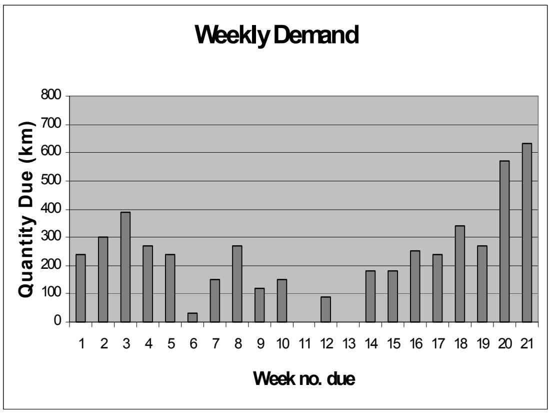
| Cable Description | Customer | Weekly Demand | | | Totals | |
|---|---|---|---|---|---|---|
| | | Avg. | SD | CV (%) | Demand (km) | Orders |
| SF White DW | Clarke Cable | 3 | 7 | 251 | 58 | 3 |
| White DW | Clarke Cable | 0 | 2 | 458 | 10 | 1 |
| Grey DW | Clarke Cable | 1 | 4 | 458 | 20 | 1 |
| Black 5000M DW | Marbourne/Clarke Cable | 8 | 11 | 133 | 171 | 11 |
| White 3000M | Marbourne | 1 | 5 | 321 | 30 | 2 |
| Max White 5000M | Marbourne | 3 | 8 | 317 | 53 | 2 |
| Light Grey 3000M | Marbourne | 1 | 5 | 458 | 21 | 1 |
| Light Grey 5000M | Marbourne | 1 | 3 | 458 | 15 | 1 |
| Black DW SPCL TOL | Masterplug | 6 | 11 | 201 | 116 | 6 |
| Orange DW SPCL TOL | Masterplug | 7 | 20 | 283 | 149 | 3 |
| AG Blue DW | Masterplug | 7 | 15 | 208 | 156 | 3 |
| Black 100M | Rs | 5 | 9 | 177 | 109 | 5 |
| White 100M | Rs | 3 | 7 | 251 | 57 | 3 |
| Grey 100M | Rs | 1 | 4 | 458 | 19 | 1 |
| Orange 100M | Rs | 1 | 4 | 458 | 20 | 1 |
| **Total** | **15 end items** | **48** | **41** | **86** | **1002** | **44** |
| **Average per end item** | | **3** | | **326** | **67** | **3** |

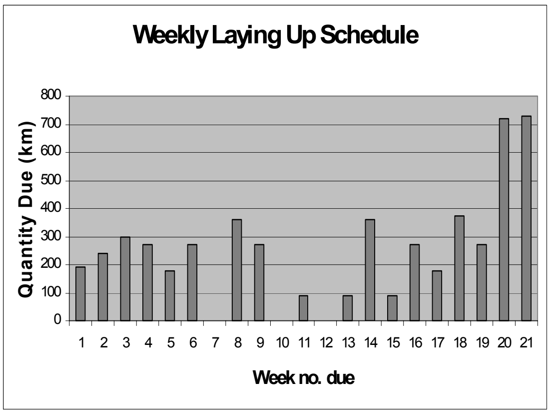
# Appendix 8 – TB Demand Amplification Charts

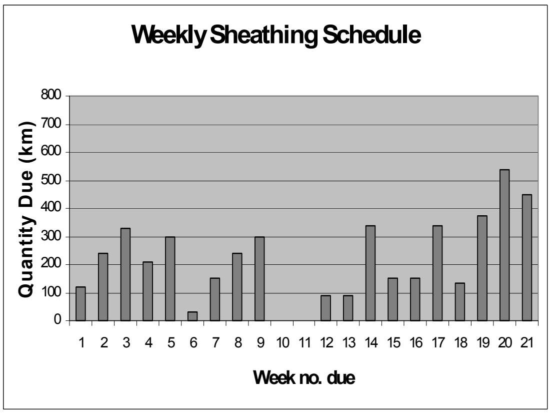
*Notes:*

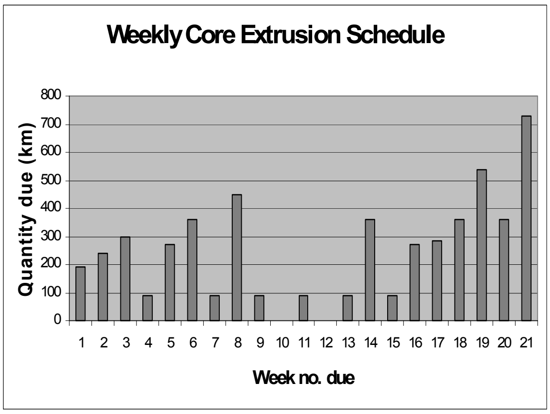
The scheduled quantities at core extrusion and bunching were three times finished cable length because there are three cores in each cable. To ensure the scheduled quantities at these processes were in units equivalent to finished cable length the length of one core only and one third of the bunch length were taken.

## Demand Amplification for 3183Y1.00mm Cable Subject to FPp due Between 4 January and 29 May 1999

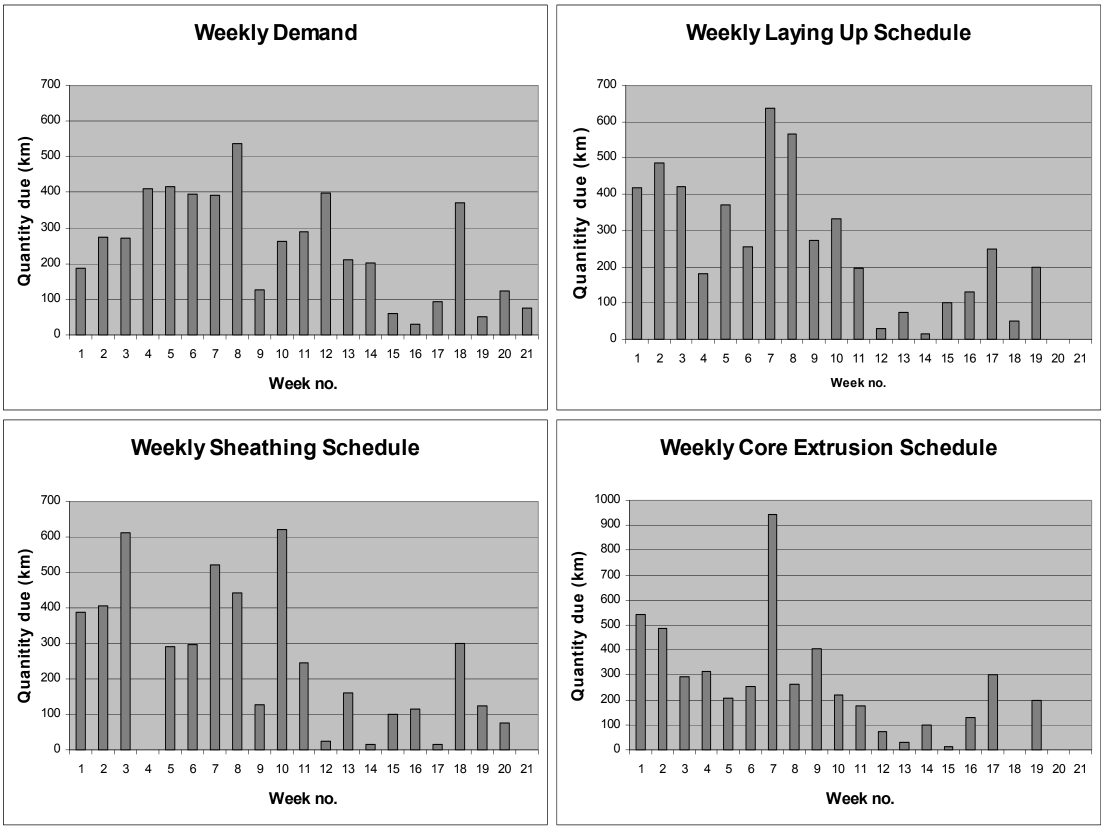


# Demand Amplification for 3183Y1.00mm Cable Subject to MTO due Between 4 January and 29 May 1999




***Notes:***

The scale for the cable quantity due on the core extrusion schedule plot is different to the other plots. It has a maximum reading of 1000km rather than 700km for the others.

# Appendix 9 – TB Customer Service Measures

- At TB the transit time for domestic cable orders was less than 24 hours therefore the delivery due date, as stated on the customer order, was the same as the ex-works due date. However, for the export orders in the MTO UoA the transit times were 4 or 5 weeks. Therefore the ex-works due date was taken as the delivery due date for all orders with the proviso that for export there was a transit time

- A number of the archived customer orders subject to MTO were missing. Further, other MTO order were excluded from the order lead-time measure because they were ordered before Christmas and due after therefore the order lead-time would have been artificially long.

- When measuring the order lead-time and delivery reliability a tolerance of 5% was allowed on the quantity delivered. Therefore the order was only considered delivered when 95% of the order quantity had been delivered or, in the case where 95% was never delivered, when the *last delivery* had been made on the order. .

# Appendix 10 – TB Degree of Commonality Calculations

The Degree of commonality index (as defined in the glossary Appendix 1) was calculated across each UoA for BOM levels 1, 2 and 3 components. The following formula was used based on Collier's formula:

The average number of incidences of the distinct component parts at BOM level 'x' for a particular UoA

$$= \frac{\text{total no. of incidences of BOM level 'x' components across end items}}{\text{no of distinct components at BOM level 'x' across end items}}$$

The table below shows the **d**egree of commonality index calculations for each UoA

| | MTO | FPp | MTS |
|---|---|---|---|
| **Total no. of incidences of BOM Level 1 components** | **56** | **10** | **43** |
| **No of distinct components at BOM level 1** | **25** | **6** | **21** |
| **Total no. of incidences of BOM Level 2 components** | **90** | **27** | **71** |
| **No of distinct components at BOM level 2** | **26** | **10** | **12** |
| **Total no. of incidences of BOM Level 3 components** | **108** | **30** | **90** |
| **No of distinct components at BOM level 3** | **7** | **6** | **6** |
| Degree of commonality index | | | |
| BOM level 1 packaging components | **2 (12%)** | **2 (33%)** | **2 (14%)** |
| BOM level 2 sheath extrusion components | **4 (19%)** | **3 (54%)** | **6 (39%)** |
| BOM level 3 core extrusion components | **15 (86%)** | **5 (100%)** | **15 (100%)** |
| Over levels 1, 2 and 3 | **4 (24%)** | **3 (61%)** | **5 (35%)** |
| Upper Bound **- no. of end items** | **18** | **5** | **15** |

# Appendix 11 – TB Throughput Efficiency Measure

**Sampling jobs for Throughput Efficiency Measurement**

Due to the laborious nature of tracing jobs through the factory the total number of jobs to be traced was limited to twelve. For the purposes of comparison between the FPp and MTO UoA the jobs sampled from the MTO UoA were restricted to those supplied to VP. In general jobs were sampled taking into account a number of factors to minimise the effect of variables, other than the inventory management policies themselves:

- To avoid the effect of the Christmas vacation but still focus on the early application of FPp the jobs sampled were output from sheathing towards the end of January, through February and beginning of March.

- To account for the variable nature of the WIP levels it was attempted to sample jobs from all three UoA that were output from sheathing at the same time in the month, approximately end of January, middle of February and beginning of March.

- The quantity ordered was between 30 and 60 km, well in excess of the 15 km MOQ.

**Notes on Throughput Efficiency Calculation**

- The elapsed time was measured over the factory operating hours from 7:00am Monday to 7:00am Saturday

- The three cores are often core extruded simultaneously. In this situation it is advisable when calculating throughput efficiency to take the longest processing time. Therefore the processing time for the green yellow core was used because it is normally processed at the slowest rate.

- The date the finished cable was booked into stores was available for the cables subject to FPp but not for those subject to MTO. Further the time of booking into finished goods stores was not known therefore this data could not be used for calculating elapsed time excluding time in finished good stock.

- Only the date, not the time, of despatch was known so for every order it was assumed that it was despatched at 12 noon. Further, where an order was despatched in two lots the date of the last despatch was taken to calculate the elapsed time.

## Example of throughput efficiency measurement sheet:

**Throughput Efficiency**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Unit of Analysis: | | **Form Postponement** | | | | | Customer | | **VOLEX P'CORDS** | |
| Product description: | | 3183Y1.00FTGY-VP | | | | | Product code | | 20F224381081-VP | |
| Quantity ordered: | | **60km** | | | | | Factory order | | HO27687/0104 | |
| Due Delivery Day: | | **Friday 29 January** | | | | | | | | |
| | | | | | Start | | End | | Duration | Comments |
| Description of work | | | | | Time | Date | Time | Date | (hours) | |
| Extrude cores | ● | □ | ⇨ | ▽ | 2:00 | 28-Jan-99 | 4:00 | 28-Jan-99 | 2.00 | |
| Transport to Laying Up | ○ | □ | ➡ | ▽ | | | | | | |
| Store at Laying Up | ○ | □ | ⇨ | ▼ | | | | | 12.50 | |
| Lay up cores | ● | □ | ⇨ | ▽ | 16:30 | 28-Jan-99 | 23:00 | 28-Jan-99 | 6.50 | |
| | | | | | 7:15 | 29-Jan-99 | 9:15 | 29-Jan-99 | 2.00 | |
| Transport to Sheathing | ○ | □ | ➡ | ▽ | | | | | | |
| Store at Sheathing | ○ | □ | ⇨ | ▼ | | | | | 10.75 | |
| Sheath laid up cable | ● | □ | ⇨ | ▽ | 11:45 | 29-Jan-99 | 17:00 | 29-Jan-99 | 5.25 | |
| Test cable | ○ | ■ | ⇨ | ▽ | | | | | | |
| Transport to Warehouse | ○ | □ | ➡ | ▽ | | | | | | |
| Store in warehouse | ○ | □ | ⇨ | ▼ | | 30-Jan-99 | | | | w/e is 30/31 Jan |
| Despatch to customer | ○ | □ | ➡ | ▽ | | 01-Feb-99 | 60km | | 19.00 | |
| | ○ | Operation | | | | | | | | |
| | | □ | Inspection | | Total value added time (hrs) | | | | 15.75 | |
| | | | ⇨ | Transport | Total time elapsed (hrs) | | | | 58 | |
| | | | ▽ | Storage | Throughput Efficiency | | | | 27% | |
| | | | | | Excluding time in finished goods | | | | | |
| | | | | | Total time elapsed (hrs) | | | | 39 | |
| | | | | | Throughput Efficiency | | | | 40% | |

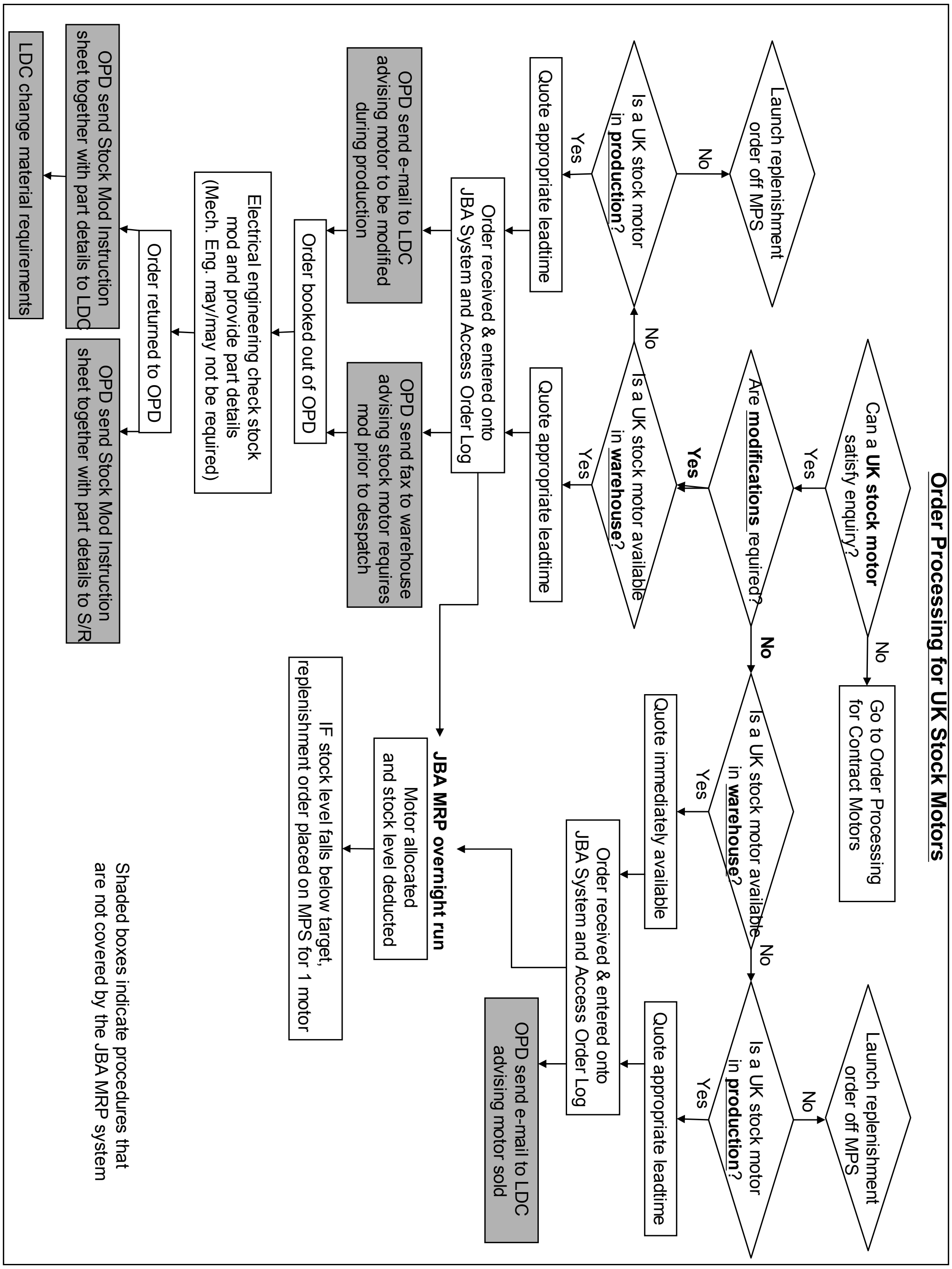
# Appendix 12 – BC Change Content Data

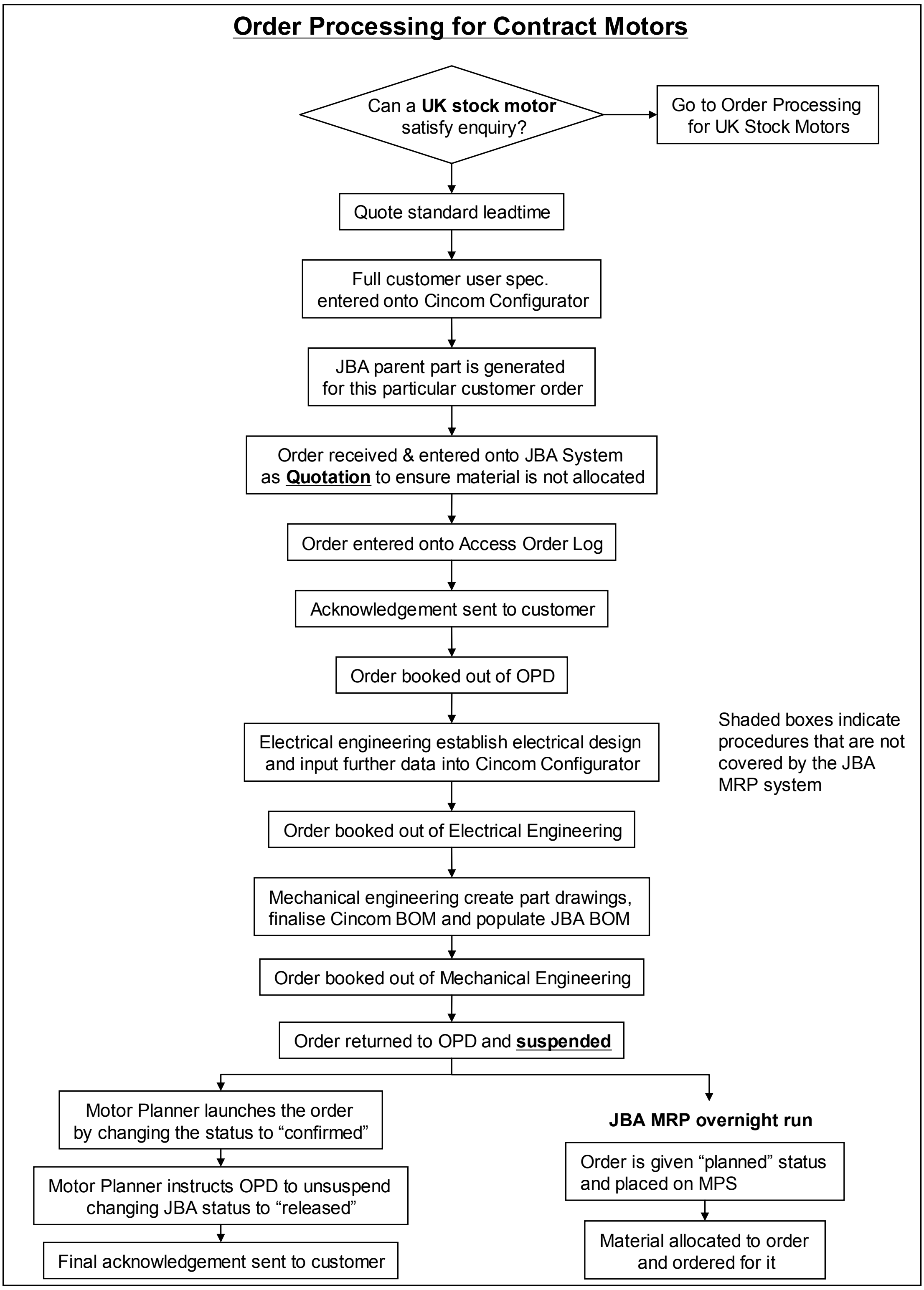
**Stock Modification Details**

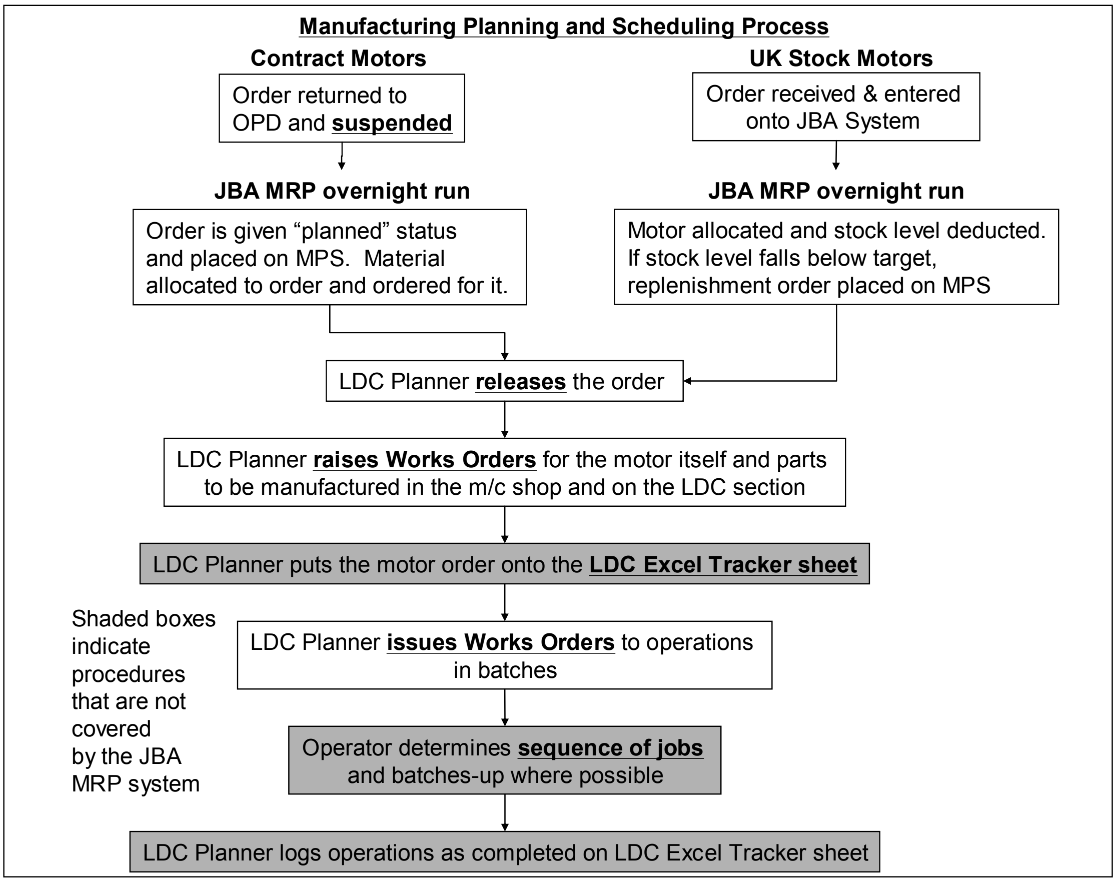
The stock modifications normally involved removing parts, which clearly was removing value already added. Indeed, as the summary of modifications in the table below illustrates, almost half (24) of the 60 motors subjected to stock modifications involved motor strip-downs. Motor strip-downs required between 4 hours and 3 working days depending on the precise modification and the motor size. Commonly these modifications involved a magnet main pole winding change or fitting thermistors.

**Summary of the 60 stock modifications due between 01/07/01 and 30/06/02**

| Parts involved | Stock Mod Type | No. of Motors | Strip-down? |
|---|---|---|---|
| Data plate only | Re-stamp data plate only | 16 | No |
| Magnet body assembly parts (25 motors) | Main pole coil change | 8 | Yes |
| | Main pole bore change | 4 | Yes |
| | Pre-wire for brush detection system | 2 | Yes |
| | Brushes change | 1 | No |
| | Thermistor change | 14 | Yes |
| Final assembly parts only | Various | 19 | No |


Order Processing for UK Stock Motors
Can a UK stock motor satisfy enquiry?
Yes
No
Go to Order Processing for Contract Motors
Are modifications required?
Yes
No
Is a UK stock motor available in warehouse?
Yes
No
Quote appropriate leadtime
Order received & entered onto JBA System and Access Order Log
OPD send fax to warehouse advising stock motor requires mod prior to despatch
Order booked out of OPD
Electrical engineering check stock mod and provide part details (Mech. Eng. may/may not be required)
Order returned to OPD
OPD send Stock Mod Instruction sheet together with part details to S/R
Is a UK stock motor in production?
Yes
No
Launch replenishment order off MPS
Quote appropriate leadtime
Order received & entered onto JBA System and Access Order Log
OPD send e-mail to LDC advising motor to be modified during production
OPD send Stock Mod Instruction sheet together with part details to LDC
LDC change material requirements
Is a UK stock motor available in warehouse?
Yes
No
Quote immediately available
Order received & entered onto JBA System and Access Order Log
Is a UK stock motor in production?
Yes
No
Launch replenishment order off MPS
Quote appropriate leadtime
OPD send e-mail to LDC advising motor sold
JBA MRP overnight run
Motor allocated and stock level deducted
IF stock level falls below target, replenishment order placed on MPS for 1 motor
Shaded boxes indicate procedures that are not covered by the JBA MRP system


Order Processing for Contract Motors
Can a UK stock motor satisfy enquiry?
Go to Order Processing for UK Stock Motors
Quote standard leadtime
Full customer user spec. entered onto Cincom Configurator
JBA parent part is generated for this particular customer order
Order received & entered onto JBA System as Quotation to ensure material is not allocated
Order entered onto Access Order Log
Acknowledgement sent to customer
Order booked out of OPD
Electrical engineering establish electrical design and input further data into Cincom Configurator
Order booked out of Electrical Engineering
Mechanical engineering create part drawings, finalise Cincom BOM and populate JBA BOM
Order booked out of Mechanical Engineering
Order returned to OPD and suspended
Motor Planner launches the order by changing the status to “confirmed”
Motor Planner instructs OPD to unsuspend changing JBA status to “released”
Final acknowledgement sent to customer
JBA MRP overnight run
Order is given “planned” status and placed on MPS
Material allocated to order and ordered for it
Shaded boxes indicate procedures that are not covered by the JBA MRP system


Manufacturing Planning and Scheduling Process
Contract Motors
UK Stock Motors
Order returned to OPD and suspended
Order received & entered onto JBA System
JBA MRP overnight run
JBA MRP overnight run
Order is given "planned" status and placed on MPS. Material allocated to order and ordered for it.
Motor allocated and stock level deducted. If stock level falls below target, replenishment order placed on MPS
LDC Planner releases the order
LDC Planner raises Works Orders for the motor itself and parts to be manufactured in the m/c shop and on the LDC section
LDC Planner puts the motor order onto the LDC Excel Tracker sheet
Shaded boxes indicate procedures that are not covered by the JBA MRP system
LDC Planner issues Works Orders to operations in batches
Operator determines sequence of jobs and batches-up where possible
LDC Planner logs operations as completed on LDC Excel Tracker sheet

# Appendix 13 – BC Demand Measures

**Delivery Due Date**

In the case of *domestic* orders the acknowledged due date was the promised delivery date to the customer, however in the case of *export* orders it was the 'ready for shipment date' or the date the packing company completed the packing. Therefore, the acknowledged due date (effectively the ex-works due date) was taken for all orders with the proviso that for export orders there was a transit time. The transit time for domestic orders was no more than 5 days, therefore negligible since demand was measured on a monthly basis.

**The demand measures for the ETO unit of analysis for orders due between 1st July '01 and 30th June '02**

| Cincom No | Description | Customer | Monthly Demand | | | Volume | Orders |
|---|---|---|---|---|---|---|---|
| | | | Avg | SD | CV (%) | | |
| M007657/01 M007658/01 | UK 132K IP23 | B.W.E Ltd | 0.17 | 0.58 | 346 | 2 | 2 |
| M007736/01 | | Awa Qingdao Paper Co Ltd | 0.08 | 0.29 | 346 | 1 | 1 |
| M007424/01 | UK 132L IP23 | Controline | 0.25 | 0.87 | 346 | 3 | 1 |
| M007431/01 | UK 132L IP23 | Aeromatic Fielder | 0.08 | 0.29 | 346 | 1 | 1 |
| M007534/01 | UK 132L IP23 | Dowding & Mills | 0.17 | 0.58 | 346 | 2 | 1 |
| M007612/01 | UK 132L IP23 | Harland Simon | 0.08 | 0.29 | 346 | 1 | 1 |
| M007648/01 | UK 132L IP23 | Harland Simon | 0.08 | 0.29 | 346 | 1 | 1 |
| M007656/01 | UK 132L IP23 | Eurotherm Drives | 0.17 | 0.58 | 346 | 2 | 1 |
| M007687/01 | UK 132L IP23 | U.M.I.S.T | 0.17 | 0.58 | 346 | 2 | 1 |
| M007688/01 | UK 132L IP20 | U.M.I.S.T | 0.08 | 0.29 | 346 | 1 | 1 |
| M007711/01 | USA L2113ATZ IP23 | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007715/01 | UK 132L IP55 | Control Techniques | 0.08 | 0.29 | 346 | 1 | 1 |
| M007434/01 | UK 132M IP23 | Boulting Group | 0.08 | 0.29 | 346 | 1 | 1 |
| M007531/01 | UK 132M IP23 | B.W.E Ltd | 0.08 | 0.29 | 346 | 1 | 1 |
| M007533/01 | USA M2112ATZ IP23 | Brook Hansen Canada | 0.08 | 0.29 | 346 | 1 | 1 |
| M007552/01 | UK 132M IP23 | Aeromatic Fielder | 0.08 | 0.29 | 346 | 1 | 1 |
| M007662/01 | UK 132M IP23 | UCB Films | 0.08 | 0.29 | 346 | 1 | 1 |
| M007691/01 | UK 132M IP23 | Woywod | 0.08 | 0.29 | 346 | 1 | 1 |
| M007692/01 | UK 132M IP23 | Alstom Repair - S-Africa | 0.08 | 0.29 | 346 | 1 | 1 |
| M007703/01 | UK 132M IP23 | Eurotherm Drives | 0.08 | 0.29 | 346 | 1 | 1 |
| M007554/01 | UK 132S IP23 | Brook Hansen France | 0.08 | 0.29 | 346 | 1 | 1 |
| M007611/01 | UK 132S IP23 | Freightliner | 0.08 | 0.29 | 346 | 1 | 1 |
| M007640/01 | UK 132S IP23 | Andantex Kinematic | 0.08 | 0.29 | 346 | 1 | 1 |

| Cincom No | Description | Customer | Monthly Demand | | | Volume | Orders |
|---|---|---|---|---|---|---|---|
| | | | Avg | SD | CV (%) | | |
| M007669/01 | UK 132S IP23 | Sherkate Taavoni (Iran) | 0.08 | 0.29 | 346 | 1 | 1 |
| M007670/01 | UK 132S IP23 | Sherkate Taavoni (Iran) | 0.08 | 0.29 | 346 | 1 | 1 |
| M007671/01 | UK 132S IP23 | Sherkate Taavoni (Iran) | 0.08 | 0.29 | 346 | 1 | 1 |
| M007698/01 | UK 132S IP23 | Harland Simon | 0.08 | 0.29 | 346 | 1 | 1 |
| M007735/01 | UK 132S IP23 | Eurotherm Drives | 0.08 | 0.29 | 346 | 1 | 1 |
| M007737/01 | UK 132S IP23 | P.T.I Japan | 0.33 | 1.15 | 346 | 4 | 1 |
| M007520/01 | UK 160K IP23 | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007608/01 M007720/01 | USA K2510ATZ IP55 | Medway Rewinds | 0.42 | 1.16 | 279 | 5 | 2 |
| M007616/01 | UK 160K IP55 | Taylor & Goodman | 0.08 | 0.29 | 346 | 1 | 1 |
| M007617/01 | UK 160K IP55 | Aeromatic Fielder | 0.08 | 0.29 | 346 | 1 | 1 |
| M007626/01 | UK 160K IP23 | A.P.V Baker | 0.08 | 0.29 | 346 | 1 | 1 |
| M007466/01 | UK 160L IP23 | Dolphin Packaging | 0.08 | 0.29 | 346 | 1 | 1 |
| M007543/01 | UK 160L IP23 | Intercontinental Development Company | 0.08 | 0.29 | 346 | 1 | 1 |
| M007558/01 | UK 160L IP23 | DCB Controls (Pty) | 0.08 | 0.29 | 346 | 1 | 1 |
| M007607/01 | UK 160L IP23 | Kirkby Lindsey | 0.17 | 0.58 | 346 | 2 | 1 |
| M007645/01 | UK 160L IP23 | Eurotherm Drives | 0.17 | 0.58 | 346 | 2 | 1 |
| M007717/01 | UK 160L IP55 | Control Techniques | 0.17 | 0.58 | 346 | 2 | 1 |
| M007525/01 | USA M2511ATZ IP55 | Brook Hansen Canada | 0.08 | 0.29 | 346 | 1 | 1 |
| M007532/01 | USA M2511ATZ IP23 | Brook Hansen Canada | 0.08 | 0.29 | 346 | 1 | 1 |
| M007618/01 M007675/01 | UK 160M/19 IP23 | A.P.V Baker | 0.17 | 0.39 | 234 | 2 | 2 |
| M007638/01 | UK 160M/20 | Midland Motor Rewinds | 0.08 | 0.29 | 346 | 1 | 1 |
| M007652/01 | UK 160M IP23 | Thompson Friction Welding | 0.08 | 0.29 | 346 | 1 | 1 |
| M007696/01 | UK 160M IP55 | Wyko | 0.08 | 0.29 | 346 | 1 | 1 |
| M007704/01 M007705/01 | UK 160M IP23 | Thompson Friction Welding | 0.58 | 2.02 | 346 | 7 | 2 |
| M007706/01 | UK 160M IP23 | Nuova Ceam | 0.08 | 0.29 | 346 | 1 | 1 |
| M007423/01 | UK 160S IP23 | Michelin Tyre | 0.08 | 0.29 | 346 | 1 | 1 |
| M007444/01 | UK 160S IP23 | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007507/01 | UK 160S IP23 | Control & Power Eng | 0.08 | 0.29 | 346 | 1 | 1 |
| M007521/01 | UK 160S C IP55 | Portals | 0.08 | 0.29 | 346 | 1 | 1 |
| M007523/01 | UK 160S IP55 | Alstom Maintenance & Services | 0.08 | 0.29 | 346 | 1 | 1 |
| M007542/01 | UK 160S IP23 | Intercontinental Development Company | 0.08 | 0.29 | 346 | 1 | 1 |
| M007547/01 | USA S2511ATZ IP23 | Brook Inc USA | 0.25 | 0.87 | 346 | 3 | 1 |
| M007553/01 | UK 160S | Birmingham Pumps | 0.08 | 0.29 | 346 | 1 | 1 |

| Cincom No | Description | Customer | Monthly Demand | | | Volume | Orders |
|---|---|---|---|---|---|---|---|
| | | | Avg | SD | CV (%) | | |
| M007694/01 | UK 160S IP23 | Aeromatic Fielder | 0.08 | 0.29 | 346 | 1 | 1 |
| M007345/01 | USA L2813ATZ, | Eaton Cutler Hammer | 0.08 | 0.29 | 346 | 1 | 1 |
| M007548/01 | USA L2813ATZ IP23 | Brook Inc USA | 0.25 | 0.87 | 346 | 3 | 1 |
| M007619/01 | UK 180L IP23 | Carrington Wire | 0.25 | 0.87 | 346 | 3 | 1 |
| M007621/01 | UK 180L IP23 | Fenner | 0.08 | 0.29 | 346 | 1 | 1 |
| M007664/01 | UK 180L IP55 | Cegelec Maintenance & Services | 0.17 | 0.58 | 346 | 2 | 1 |
| M007716/01 | UK 180L IP55 | Control Techniques | 0.17 | 0.58 | 346 | 2 | 1 |
| M007740/01 | UK 180L IP23 | Georgia-Pacific | 0.08 | 0.29 | 346 | 1 | 1 |
| M007445/01 | UK 180M IP23 | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007467/01 | UK 180M IP23 | Hull Bulk Handling | 0.08 | 0.29 | 346 | 1 | 1 |
| M007536/01 | UK 180M IP23 | Eurotherm Drives | 0.08 | 0.29 | 346 | 1 | 1 |
| M007551/01 | UK 180M IP23 | Eurotherm Drives | 0.08 | 0.29 | 346 | 1 | 1 |
| M007646/01 | UK 180M IP23 | Eurotherm Drives | 0.17 | 0.58 | 346 | 2 | 1 |
| M007683/01 | USA M2812ATZ . | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007684/01 | UK 180M IP23 | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007714/01 | UK 180M IP55 | Control Techniques | 0.08 | 0.29 | 346 | 1 | 1 |
| M007422/01 | UK 180S | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007430/01 | USA S2811ATZ IP23 | Brook Inc USA | 0.17 | 0.58 | 346 | 2 | 1 |
| M007435/01 | UK 180S IP23 | Aeromatic Fielder | 0.08 | 0.29 | 346 | 1 | 1 |
| M007469/01 | UK 180S IP23 | Controline | 0.17 | 0.58 | 346 | 2 | 1 |
| M007625/01 | UK 180S IP23 | Parkgate & Co | 0.08 | 0.29 | 346 | 1 | 1 |
| M007643/01 | UK 180S IP55 | Capitan (Europe) | 0.17 | 0.58 | 346 | 2 | 1 |
| M007732/01 | UK 180S | Brook Inc USA | 0.17 | 0.58 | 346 | 2 | 1 |
| M007427/01 | UK 200L IP23 | Hall Rewinds | 0.08 | 0.29 | 346 | 1 | 1 |
| M007428/01 | UK 200L IP23 | Rexnord - Stephan Werke | 0.08 | 0.29 | 346 | 1 | 1 |
| M007465/01 | UK 200L IP23 | Dolphin Packaging | 0.08 | 0.29 | 346 | 1 | 1 |
| M007541/01 | UK 200L IP23 | Michelin Tyre | 0.08 | 0.29 | 346 | 1 | 1 |
| M007544/01 | UK 200L IP23 | Intercontinental Development Company | 0.08 | 0.29 | 346 | 1 | 1 |
| M007559/01 | UK 200L IP23 | IMI Yorkshire Copper Tube | 0.08 | 0.29 | 346 | 1 | 1 |
| M007628/01 | UK 200L IP23 | Nuova Ceam | 0.08 | 0.29 | 346 | 1 | 1 |
| M007661/01 | UK 200L IP23 | B.W.E Ltd | 0.08 | 0.29 | 346 | 1 | 1 |
| M007667/01 | UK 200L IP23 | Sherkate Taavoni (Iran) | 0.17 | 0.58 | 346 | 2 | 1 |
| M007699/01 | UK 200L IP23 | Brook Hansen Canada | 0.08 | 0.29 | 346 | 1 | 1 |
| M007708/01 | UK 200L IP23 | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007495/01 | UK 200M IP23 | Unico | 0.08 | 0.29 | 346 | 1 | 1 |
| M007538/01 | USA M3212ATZ IP23 | Brook Hansen Canada | 0.33 | 1.15 | 346 | 4 | 1 |

| Cincom No | Description | Customer | Monthly Demand | | | Volume | Orders |
|---|---|---|---|---|---|---|---|
| | | | Avg | SD | CV (%) | | |
| M007549/01 | USA M3212ATZ IP23 | Brook Inc USA | 0.25 | 0.87 | 346 | 3 | 1 |
| M007637/01 | UK 200M IP23 | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007655/01 | UK 200M IP23 | Eurotherm Drives | 0.08 | 0.29 | 346 | 1 | 1 |
| M007659/01 M007660/01 | UK 200M IP23 | B.W.E Ltd | 0.17 | 0.58 | 346 | 2 | 2 |
| M007673/01 | UK 200M IP23 | Webster & Bennett | 0.08 | 0.29 | 346 | 1 | 1 |
| M007417/01 | UK 200S/11 IP23 | A.P.V Baker | 0.08 | 0.29 | 346 | 1 | 1 |
| M007627/01 | | P.T.Indocement Tunggal | 0.08 | 0.29 | 346 | 1 | 1 |
| M007639/01 | UK 200S IP23 | Newsquest (Oxfordshire) | 0.08 | 0.29 | 346 | 1 | 1 |
| M007642/01 | UK 200S IP44 | Eurotherm Drives | 0.25 | 0.87 | 346 | 3 | 1 |
| M007647/01 | UK 200S IP23 | Harland Simon | 0.08 | 0.29 | 346 | 1 | 1 |
| M007649/01 | UK 200S IP23 | Harland Simon | 0.08 | 0.29 | 346 | 1 | 1 |
| M007668/01 | UK 200S IP23 | Goss Graphics | 0.08 | 0.29 | 346 | 1 | 1 |
| M007679/01 | UK 200S/10 IP23 | Gibbons Drive Systems Ltd. | 0.08 | 0.29 | 346 | 1 | 1 |
| M007689/01 | UK 200S IP23 | EFCO | 0.08 | 0.29 | 346 | 1 | 1 |
| M007739/01 | UK 200S IP23 | DCB Controls (Pty) | 0.08 | 0.29 | 346 | 1 | 1 |
| M007432/01 | MK3 225L IP23 | Thompson Friction Welding | 0.08 | 0.29 | 346 | 1 | 1 |
| M007447/01 | UK 225L IP23 | Wyko | 0.08 | 0.29 | 346 | 1 | 1 |
| M007615/01 | UK 225L IP23 | Eurotherm Drives | 0.08 | 0.29 | 346 | 1 | 1 |
| M007654/01 | UK 225L IP23 | Eurotherm Drives | 0.08 | 0.29 | 346 | 1 | 1 |
| M007470/01 | UK 225M IP23 | Nuova Ceam | 0.08 | 0.29 | 346 | 1 | 1 |
| M007610/01 | USA M3612ATZ IP55 | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007666/01 | USA M3612ATZ IP23 | Brook Hansen Canada | 0.08 | 0.29 | 346 | 1 | 1 |
| M007676/01 | UK 225M/16 IP23 | Rigid Paper | 0.08 | 0.29 | 346 | 1 | 1 |
| M007734/01 | UK 225M IP23 | Goss Graphics | 0.08 | 0.29 | 346 | 1 | 1 |
| M007329/01 | UK 225S IP23 | P.T.I Japan | 0.50 | 1.73 | 346 | 6 | 1 |
| M007401/01 | UK 225S IP23 | Goss Graphics | 0.08 | 0.29 | 346 | 1 | 1 |
| M007448/01 | UK 225S IP23 | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007522/01 | UK 225S IP23 | Medway Rewinds | 0.08 | 0.29 | 346 | 1 | 1 |
| M007540/01 | UK 225S IP23 | Alstom Repair - S-Africa | 0.08 | 0.29 | 346 | 1 | 1 |
| M007557/01 | UK 225S IP23 | Rexnord - Stephan Werke | 0.08 | 0.29 | 346 | 1 | 1 |
| M007599/01 | UK 225S IP23 | Goss Graphics | 0.17 | 0.58 | 346 | 2 | 1 |
| M007650/01 | UK 225S IP23 | Harland Simon | 0.08 | 0.29 | 346 | 1 | 1 |
| M007663/01 | UK 225S IP55 15HP | C.Y.Electrical & Cranes Co.Ltd. | 0.08 | 0.29 | 346 | 1 | 1 |

| Cincom No | Description | Customer | Monthly Demand | | | Volume | Orders |
|---|---|---|---|---|---|---|---|
| | | | Avg | SD | CV (%) | | |
| M007685/01 | UK 225S IP23 | Goss Graphics | 0.17 | 0.58 | 346 | 2 | 1 |
| M007693/01 | UK 225S IP55 | A.P.V Baker | 0.08 | 0.29 | 346 | 1 | 1 |
| M007695/01 | UK 225S IP55 | SM Cyclo UK | 0.08 | 0.29 | 346 | 1 | 1 |
| M007343/01 | USA L4012ATZ | Eaton Cutler Hammer | 0.08 | 0.29 | 346 | 1 | 1 |
| M007524/01 | UK 250L IP23 | Thompson Friction Welding | 0.08 | 0.29 | 346 | 1 | 1 |
| M007545/01 | UK 250L IP23 | Brook Inc USA | 0.08 | 0.29 | 346 | 1 | 1 |
| M007653/01 | UK 250L IP55 | Freightliner | 0.08 | 0.29 | 346 | 1 | 1 |
| M007509/01 | UK 250M IP23 | A.P.V Baker | 0.08 | 0.29 | 346 | 1 | 1 |
| M007609/01 | UK 250M IP23 | Associated British Ports | 0.08 | 0.29 | 346 | 1 | 1 |
| M007341/01 | USA S4011ATZ | Eaton Cutler Hammer | 0.08 | 0.29 | 346 | 1 | 1 |
| M007602/01 M007604/01 M007605/01 | USA S4011ATZ | Brook Inc USA | 0.67 | 2.31 | 346 | 8 | 3 |
| M007620/01 | UK 250S IP55 | Alstom Maintenance & Services | 0.08 | 0.29 | 346 | 1 | 1 |
| M007690/01 | UK 250S IP23 | EFCO | 0.08 | 0.29 | 346 | 1 | 1 |
| M007707/01 | UK 250S IP23 | Wyko | 0.08 | 0.29 | 346 | 1 | 1 |
| M007629/01 | UK 280L IP23 | Castle Cement | 0.08 | 0.29 | 346 | 1 | 1 |
| M007702/01 | UK 280L IP23 | Taylor & Goodman | 0.08 | 0.29 | 346 | 1 | 1 |
| M007613/01 | UK 280M IP23 | Alstom Repairs | 0.08 | 0.29 | 346 | 1 | 1 |
| M007672/01 | UK 280M IP23 | Tyneside Safety Glass | 0.08 | 0.29 | 346 | 1 | 1 |
| M007546/01 | USA SC4411ATZ IP23 **LUMBER DUTY** | Brook Inc USA | 0.17 | 0.58 | 346 | 2 | 1 |
| M007421/01 M007641/01 | UK 280X IP55 | G.E. Mitchell | 0.17 | 0.39 | 234 | 2 | 2 |
| M007450/01 M007451/01 M007452/01 M007678/01 | USA XC4413ATDZ IP20 | Brook Inc USA | 0.67 | 0.98 | 148 | 8 | 4 |
| M007709/01 M007710/01 | USA XC4413ATZ | Brook Inc USA | 0.17 | 0.58 | 346 | 2 | 2 |
| M007339/01 | UK 355M | Eaton Cutler Hammer | 0.08 | 0.29 | 346 | 1 | 1 |
| M007446/01 | UK 355M IP23 | Froude Consine | 0.17 | 0.58 | 346 | 2 | 1 |
| M007636/01 | UK 355M IP23 | Trans Agric Diesel | 0.08 | 0.29 | 346 | 1 | 1 |
| M007644/01 | UK 355M IP23 | Froude Consine | 0.08 | 0.29 | 346 | 1 | 1 |
| M007276/01 | UK 355S IP23 | Brook Inc USA | 0.33 | 0.78 | 234 | 4 | 2 |
| M007299/01 | UK 355S IP23 | Brook Inc USA | 0.17 | 0.58 | 346 | 2 | 2 |
| M007614/01 | UK 355S IP23 | Trans Agric Diesel | 0.08 | 0.29 | 346 | 1 | 1 |
| M007630/01 | UK 355S IP23 | Rockwell Automation | 0.08 | 0.29 | 346 | 1 | 1 |
| | **Total** | | **19.08** | **10.07** | **53** | **229** | **169** |
| | **Average per motor spec.** | | | | **343** | **1.5** | |

### The demand measures for the MTO unit of analysis for orders due between 1st July '01 and 30th June '02

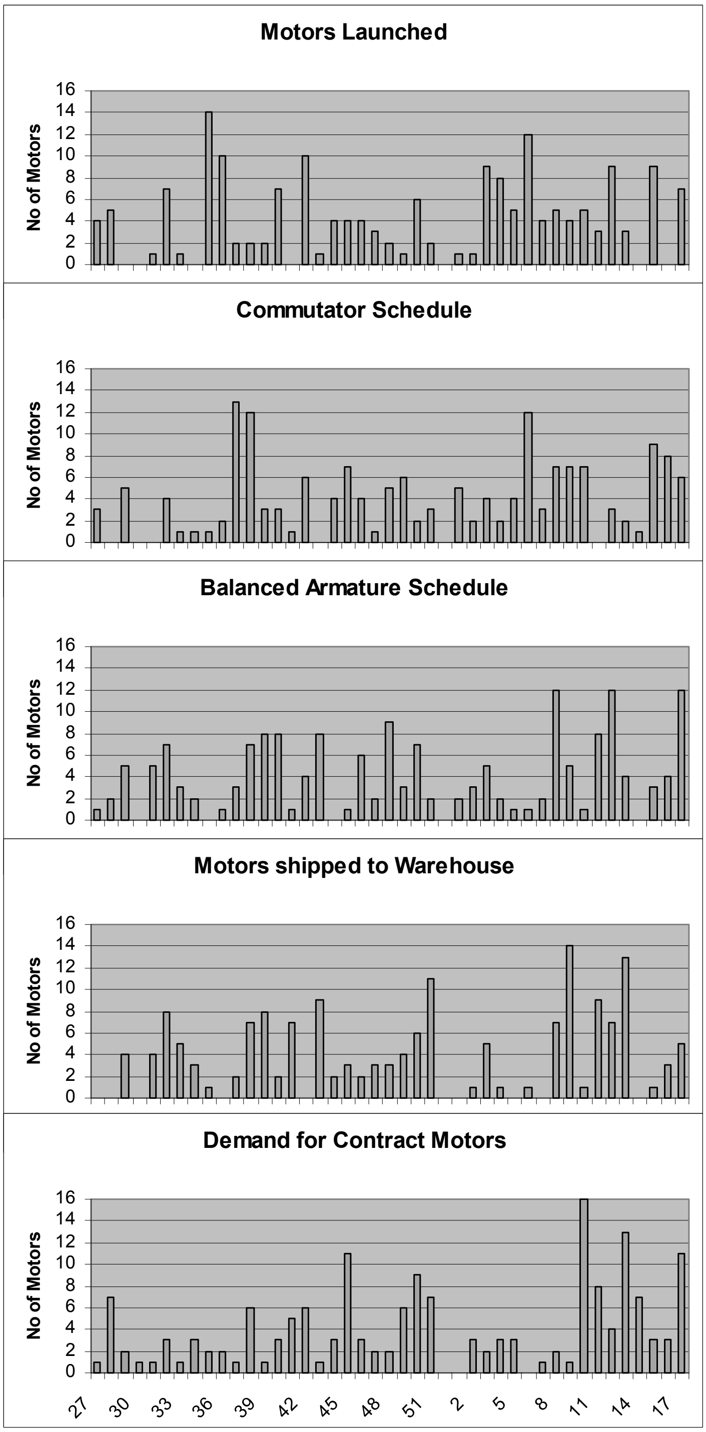
| Spec. No. | Description | No of Orders | Volume Demand | Monthly Demand | | |
|---|---|---|---|---|---|---|
| | | | | Av. | SD | CV (%) |
| 99040202 | M2112ATZ 30HP | 1 | 2 | 0.17 | 0.58 | 346 |
| 99040203 | M2511ATZ 50HP | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040204 | M2511ATZ 60HP | 2 | 4 | 0.33 | 0.89 | 266 |
| 99040205 | M2812ATZ 75HP | 1 | 2 | 0.17 | 0.58 | 346 |
| 99040206 | M2812ATZ 100HP | 2 | 3 | 0.25 | 0.62 | 249 |
| 99040207 | S3211ATZ 125HP | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040208 | M3212ATZ 150HP | 4 | 6 | 0.50 | 0.90 | 181 |
| 99040209 | S3611ATZ 200HP | 4 | 6 | 0.50 | 0.80 | 160 |
| 99040210 | M3612ASTZ 250HP | 2 | 2 | 0.17 | 0.39 | 234 |
| 99040211 | L3612ATZ 300HP | 3 | 3 | 0.25 | 0.62 | 249 |
| 99040212 | L4012ATZ 400HP | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040214 | LC4412ATZ 600HP | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040215 | XC4413ATZ 700HP | 1 | 1 | 0.08 | 0.29 | 346 |
| **Total** | | **24** | **33** | **2.75** | **2.67** | **97** |
| **Average per motor spec.** | | | **2.5** | | | **289** |

### The demand measures for the MTS unit of analysis for orders due between 1st July '01 and 30th June '02

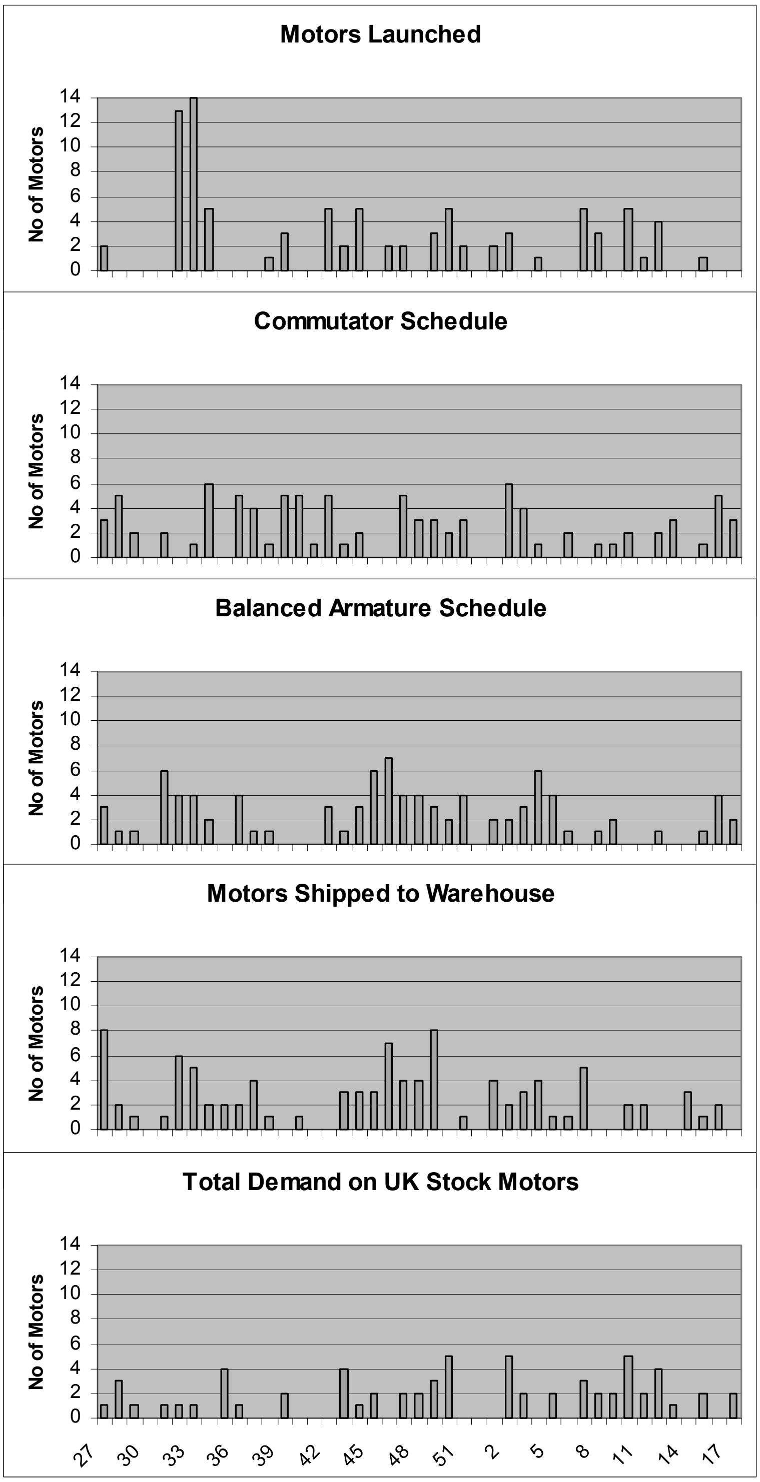
| Spec. No. | Frame Size | Power Output | No of Orders | Volume Demand | Monthly Demand | | |
|---|---|---|---|---|---|---|---|
| | | | | | Av. | SD | CV (%) |
| 99040105 | 132L | 33KW | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040105 | 132L | 33KW | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040109 | 160S | 44KW | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040115 | 160L | 47KW | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040121 | 180S | 76KW | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040123 | 180M | 79KW | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040129 | 180L | 99KW | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040131 | 200S | 110KW | 2 | 2 | 0.17 | 0.39 | 234 |
| 99040133 | 200M | 124KW | 4 | 4 | 0.33 | 0.65 | 195 |
| 99040135 | 200L | 140KW | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040137 | 225S | 169KW | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040141 | 225M | 187KW | 2 | 2 | 0.17 | 0.39 | 234 |
| 99040149 | 250M | 292KW | 3 | 3 | 0.25 | 0.45 | 181 |
| 99040151 | 250L | 320KW | 1 | 1 | 0.08 | 0.29 | 346 |
| 99040157 | 280L | 480KW | 2 | 2 | 0.17 | 0.39 | 234 |
| **Total** | | | **23** | **23** | **1.92** | **1.51** | **79** |
| **Average per motor spec.** | | | | **1.5** | | | **303** |

# Appendix 14 – BC Demand Amplification Charts

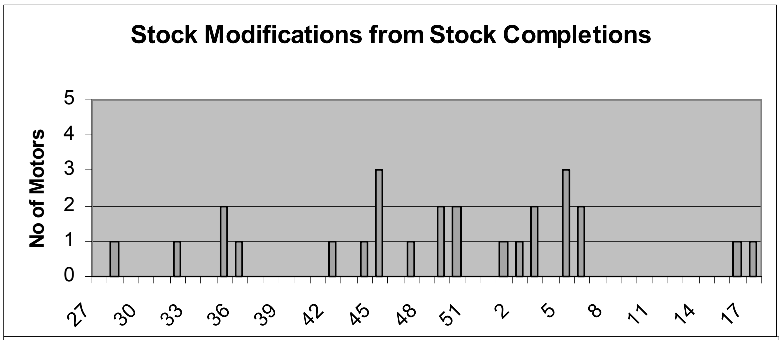
## Demand Amplification for Contract Motors (ETO) due Between 1st July '01 and 30th April'02

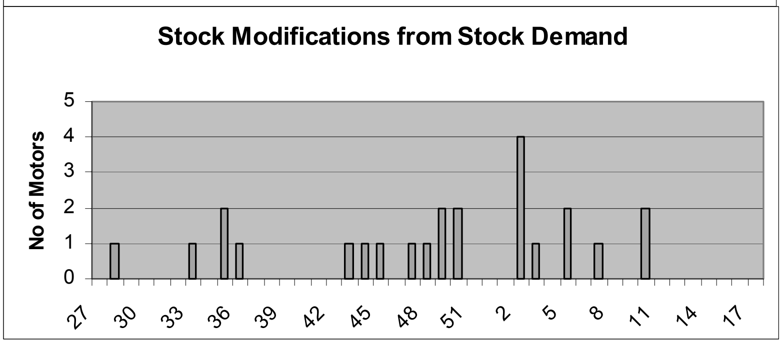


# Demand Amplification for UK Stock motors (MTS) due Between 1st July ’01 and 30th April’02



## Demand Amplification for UK Stock motors modified from stock (FPp) and due between 1st July ’01 and 30th April’02




**Demand Amplification chart notes:**

- The analysis was restricted to a ten month period due to the incomplete nature of the manufacturing schedule data for the months May and June ’02.
- The 280 and 355 motors were excluded from the demand amplification charts for the contract motors since these were generally manufactured on a lead-time 2 weeks longer than the other motors, which may have distorted the demand patterns.

# Appendix 15 – BC Customer Service Measures

**Ex-stock Availability**

The data was not available to measure ex-stock availability in terms of the proportion of enquiries for which the correct UK stock motor was available. However, two sources of data were available which gave a good indication of this measure. The first was the number of orders for UK stock motors, which were satisfied with motors from stock. Of the 59 orders for modified UK stock (FPp) motors 37 (63%) appeared on the LDC Stock Mod Record, indicating that they were satisfied with motors from stock. The remaining 22 orders were satisfied with motors in production indicating that for these orders stock motors were not available. Therefore, the ex-stock availability for the modified stock motors was 63% or less, since this measure does not take into account enquiries received, which were not converted into orders because the stock was not available.

Of the direct ex-stock (MTS) orders none appeared to be fulfilled by a motor in production (as indicated by the absence of these customer orders on the LDC Tracker sheet). Therefore, it was assumed that the correct stock motor was always available. This assumption was supported by the consistently short order lead-time, on average no more than a day, suggesting that all the motors were immediately available. Therefore, the ex-stock availability for the direct ex-stock orders (MTS) was 100% or less, since this measure did not take into account enquiries received, which were not converted into orders because the stock was not available. This appeared much higher than the ex-stock availability measured for the modified stock motors (FPp). However, the disparity in the ex-stock availability measure was difficult to explain when it was considered that the modified and direct sale motors drew from the same motor stocks. One probable explanation was that if a standard UK motor was not immediately available for a direct ex-stock sale the sale was more likely to be lost because these motors were more widely available ex-stock.

The second source of evidence showed that many enquiries did not become orders because the stock motor was not available. This evidence was supplied by the LDC Sales Manager and was the orders lost due to the non-availability of UK stock motors. Between January and November 2002, 31 orders were lost. This was less than a year period but the lost orders still equated to about half of the 59 modified stock orders, or over 100% of the 23 direct ex-stock motor orders received over the year period of the study. However, it should be noted that these lost orders are the total across both the modified stock motors and the ex-stock motors and it is not possible to apportion them between the two.

**Dates for Measuring Order Lead-time and Delivery Reliability**

In the case of export orders the acknowledged due date, found on the Order Log, is the ‘ready for shipment date’ or the date the packing company is due to completed the packing. Fortunately, the recorded despatch date on the Order Log, for export orders, is the date the order leaves the packer, therefore comparing this date with the acknowledged due date will be a good measure of delivery reliability.

In the case of domestic orders the acknowledged due date is the promised delivery date to the customer, whereas the despatch date, recorded on the Order Log, is the date the motor is received by the transport company. Unfortunately, the transit time is often in excess of 24 hours since it depends upon whether the despatch address falls within the Blackheath or Huddersfield area. For the domestic orders I was able to cross reference the despatch dates on the Order Log with the despatch dates on the despatch notes and quite often, regardless whether the motor was distributed via Huddersfield or not, the motor would spend 3 or 4 days in transit. Sadly, the despatch notes were not available for a good proportion of the orders and even when they were available the customer receipt dates were not reliably available. Suffice it to say that comparing the recorded despatch date with the acknowledged due-to-customer date is a lenient measure of delivery reliability. Similarly this applies to using the despatch date to measure order lead-time. However, the degree of leniency is similar across all UoA.

# Appendix 16 – BC BOM Analysis

**Cincom BOM limitations**

The Cincom BOMs were structured by functional elements rather than by BOM levels. This was overcome by transposing the components onto a spreadsheet, and reorganising them according to BOM level, which was indicated on the Cincom BOM.

There were no part descriptions on the Cincom BOMs therefore it was only possible to recognise parts from their part numbers and locations in a particular configuration element. The T* part numbers were standardised in generic groupings (eg all T018 numbers refer to the shaft part). However all other part numbers were not identifiable.

The Cincom BOMs only covered levels 1, 2 and 3. Infact for the magnet body assembly they did not cover 3 and for the final assembly parts they did not cover 2 or 3. The full indented BOMs had 6 levels for the commutator, 4 levels for the rest of the wound armature assembly, 4 levels for the magnet body assembly and 2 levels for the final assembly parts. The lower BOM levels for each major sub-assembly were missing, the implications were:

- All parts that were required for the commutator were missing therefore it was not possible to analyse the variety in the commutator parts. This was estimated by interviewing engineer and assessing variety in these parts for the Production Variety Funnel.

- Level 4 raw material parts required to make the unwound armature were missing. These were mostly raw materials (code 4, stocked and back-flushed) converted by the machine shop, with the notable exception of the armature laminates (code 8 MRP purchased). Therefore it was possible to analyse the armature parts from machine shop and stores with the exception of armature laminates. Instead the armature core part, made up from the armature laminates was analysed.

- Level 3 and 4 parts required to make the magnet body assembly were missing. These parts make up the magnet frame assembly and pole windings, both of which are supplied fully assembled to the magnet body assembly area. The magnet frame assembly was supplied fully assembled by machine shop and the windings were supplied by the LDC pole winding cell ready made, therefore the level 2 magnet body parts accurately represented the parts and sub-assemblies delivered to the magnet body assembly area

- Level 2 final assembly parts were missing. These were raw materials subsequently converted by the machine shop. Therefore the level 1 final assembly parts accurately represented the parts delivered to the final assembly area.

**Selection of parts for Product Design and Production Variety analysis**

A copy of the full indented BOM off the JBA MRP system was obtained for the UK stock motor 180S 76kW output (99040121). This was a standard motor and one of the most popular frame sizes overall therefore understanding the make up of this motor was particularly relevant. The equivalent Cincom BOM was detailed with part descriptions and material codes. Parts were then selected in the following way:

- All DLF (Direct Line Feed ) parts were excluded since these were trivial parts such as standard washers, and screws. DLF parts were used in high volumes normally on every motor and the supplier directly serviced the stock kept on the line.

- Material code 4 parts were excluded since they tended to be trivial such as cables, Dowel pins, and sealing plugs. Code 4 parts were raw materials kept in stock room and issued to the line in bulk. The volume useage of these parts did not warrant DLF but did justify the maintenance of a stock on the line. There were two notable exceptions the balance discs (T025) and the pole shims (sheet steel/brass used to pack back of main pole) (T046). These were included in the anlaysis because they had T* part numbers as explained below. Further, the code 4 parts in the commutator, mica vee ring and sheet were included in the production variety funnel.

- All parts with T* number were selected regardless of whether they were part of the essential basic motor or part of an optional attachment element such as the heaters, or brakes. The T* parts were the most significant parts and featured on the original design of the LDC motor. The T* parts included all parts made by Brook Crompton whether they were made in the machine shop (code 5 or Kanban parts) or made on the LDC section (code L parts). The T* parts also included many of the MRP purchased parts (code 8).

- Other MRP purchased parts with a non T* part number were also selected because quite often significant parts relating to a particular configuration element (normally an optional attachment element such as the forced vents brake or pipe adaptors) were bought-in parts with a non T* part number. The only MRP purchased parts that were deliberately excluded were the circlip extension (part of the mechanical armature), and the ball bearings at the commutator end and drive end (part of the final assembly). These parts were excluded because they could not be reliably identified by their location in the Cincom BOM.

## Parts included in the BOM analysis and their material codes

| BOM Level | Cincom Element | Material Code # | Part Type | Part Description | Generic Part No. |
|---|---|---|---|---|---|
| Armature Level 3 | SHAFT | 5 | Essential | Shaft | T018 |
| | | K/5 | Essential | Shaft Nut | T023 |
| | ARM ELEC | L | Essential | Slit Commutator | T005 |
| | | L | Essential | Arm Core | TE*ARMA |
| | | 8 | Essential | Winding Carrier Ring | T021 |
| | | K/5 | Optional | Shaft Spacer | T067 |
| | ARM MECH | K/5 | Essential | Arm Pressure Cast DE | T019 |
| | | K/5 | Optional | Arm Pressure Cast CE | T020 |
| | | K/5 | Optional | Commutator Support | T022 |
| | | 8 | Essential | Armature Key | T024 |
| Armature Level 2 | ARM ELEC | L | Essential | Arm Coil | TE*ARWA |
| | ARM MECH | 4 | Essential | Balance Disc DE | T025 |
| | | 4 | Essential | Balance Disc CE | T025 |
| | SHAFT | 8 | Optional | DE Internal Fan | T026 |
| Magnet Body Level 2 | BASE M/C | 5 | Essential | Mag Frame Assy | T008 |
| | | 8 | Essential | Interpole Mech Assy | T012 |
| | | 8 | Optional | Enclosure | T057 |
| | ARM ELEC | L | Essential | Interpole Winding | TE*NW |
| | | 8 | Essential | Brush Ring Assy | T048 |
| | | L | Optional | Compensating Winding | TE*COMA |
| | BRUSHES | 8 | Essential | Carbon Brushes | T050 |
| | CE | 5 | Essential | Bracket | T043 |
| | MAINPOLE | 8 | Essential | Mech Assy | T011 |
| | | L | Essential | Winding | TW |
| | POLE SHIMS | 4 | Essential | Pole Shims | T046 |
| | TEMP PROTECTION | 8 | Essential | Microtherms | P* |
| | HEATERS | 8 | Optional | Heater | P* |
| Final Assembly Level 1 | CE COVER | 8 | Essential | Enclosure | T057 |
| | COMMUTATOR END | K/5 | Optional | Inner Brg Cap | T028 |
| | | 5 | Optional | Outer Brg Cap | T030 |
| | | 8 | Optional | NDE Attachment | T061 |
| | | 5 | Optional | Tacho fittings or pulleys | T064 |
| | | 8 | Optional | Flange Mounting &Lifting Attach | T060 |
| | DE COVER | 8 | Essential | Enclosure | T057 |
| | DRIVE END | K/5 | Essential | Inner Brg Cap | T027 |
| | | K/5 | Essential | Outer Brg Cap | T029 |
| | | 5 | Optional | Shaft/Bearing Spacers | T067 |

| BOM Level | Cincom Element | Material Code | Part Type | Part Description | Generic Part No. |
|---|---|---|---|---|---|
| Final Assembly Level 1 | DRIVE END | 5 | Essential | Bracket | T044 |
| | | 8 | Optional | Enclosure | T057 |
| | | 5/8 | Optional | Arm Locking Clamp | T063 |
| | FORCED VENT | 8 | Optional | Unit | P* |
| | | 8 | Optional | Filter | P* |
| | | 8 | Optional | Cover | T057 |
| | | 8 | Optional | Unit and fittings | T068 |
| | | 8 | Optional | Sub Assy | T077 |
| | AIR PRESSURE SWITCH | 8 | Optional | Forced Vent Arrangement | T078 |
| | | 8 | Optional | Tube | B* |
| | | 8 | Optional | Switch | P* |
| | BRAKE | 8 | Optional | Brake | P* |
| | HEATERS | 8 | Optional | Heater | P* |
| | | 8 | Optional | Pipe Vents | T068 |
| | COOLERS | 8 | Optional | Cooler | P* |
| | | 8 | Optional | Adaptor | T068 |
| | NAMEPLATE | 8 | Essential | Lub Roller Bearing | B |
| | PIPE ADAPTORS | 8 | Optional | Enclosure | T057 |
| | | 8 | Optional | Pipe vents | T068 |
| | SHAFT | 8 | Optional | Shaft Key Ext | B * |
| | | 8 | Optional | Shaft Key | T058 |
| | TACHO | 8 | Optional | Tacho | 7.8751* |
| | TERMINAL BOX | 8 | Essential | Terminal Box Assy Complete | T073 |
| | | 8 | Essential | Base and Mounting Brkt | T052 |
| | | 8 | Essential | Centre Plate Earthing Strip | T053 |
| | | 8 | Essential | Lid | T054 |
| | | 8 | Essential | Terminal Block | T056 |
| | | 8 | Essential | Enclosure and Gasket | T057 |

| Material Code | Definition |
|---|---|
| ***L*** | Parts made on the LDC section |
| ***DLF (Direct Line Feed )*** | Parts used in high volumes normally on every motor and the supplier directly services the stock kept on the line |
| ***4*** | Raw materials kept in stock room and issued to line in bulk. The volume useage of these parts does not warrant DLF but does justify the maintenance of a stock on line |
| ***5*** | Parts made in the machine shop |
| ***K*** | Parts made in the machine shop and kept in Kanbans |
| ***8*** | Parts MRP purchased |

# Appendix 17 – BC Degree of Commonality Calculations

The Degree of commonality index (as defined in the glossary Appendix 1) was calculated across each UoA for: the finished motor; the unwound armature assembly; and the magnet body assembly. Only the distinct components in the immediate BOM level below were considered. The following formulae were used based on Collier's formula:

***Degree of commonality index for BOM level 1 components in the finished motor***

$$= \frac{\text{total no. of incidences of BOM level 1 components}}{\text{no of distinct components at BOM level 1}}$$

where BOM level 1 components = wound armature assemblies + magnet body assemblies + final assembly components

***Degree of commonality index for BOM level 3 components in the unwound armature***

$$= \frac{\text{total no. of incidences of BOM level 3 components in unwound armature}}{\text{no of distinct unwound armature components at BOM level 3}}$$

***Degree of commonality index for BOM level 2 components in the magnet body***

$$= \frac{\text{total no. of incidences of BOM level 2 components in magnet body}}{\text{no of distinct magnet body components at BOM level 2}}$$

The table below shows the degree of commonality index calculations for each UoA:

| | ***ETO*** | ***FPp*** | ***MTS*** |
|---|---|---|---|
| Total no. of incidences of Level 1 components | 3965 | 1491 | 383 |
| ***No of distinct components at level 1*** | ***894*** | ***222*** | ***141*** |
| Total no. of incidences of Level 3 components in Unwound Armature | 1433 | 590 | 148 |
| ***No. of distinct Unwound Armature components at Level 3*** | ***366*** | ***132*** | ***103*** |
| Total no. of incidences of Level 2 components in Magnet Body | 2004 | 728 | 184 |
| ***No. of distinct Magnet Body components at Level 2*** | ***516*** | ***209*** | ***140*** |
| BOM level 1 components in Finished Motor | 4.4 (3%) | 6.7 (12%) | 2.7 (19%) |
| BOM level 3 components in Unwound Armature | 3.9 (3%) | 4.5 (8%) | 1.4 (10%) |
| BOM level 2 components in Magnet Body Assembly | 3.9 (3%) | 3.5 (6%) | 1.3 (9%) |
| ***Over levels 1, 2, and 3*** | ***4 (3%)*** | ***5 (9%)*** | ***2 (13%)*** |
| Upper Bound - Finished Motors | 155 | 56 | 14 |

# Appendix 18 – BC Capacity Utilisation Measure

**The data below applies to the six month period 1st January and 30th June ’02.**

| Cell | Labour levels | Available Man-hours per week | Cycle times (min.) | Design Capacity (motors) | Average Weekly Output | *Average Weekly Capacity Utilisation* | CV |
|---|---|---|---|---|---|---|---|
| **Commutator build** | 2 | 74 | 190 | 23 | 10 | ***43%*** | 38% |
| **Armature core** | 1 | 37 | 100 | 22 | 9 | ***41%*** | 37% |
| **Armature assembly** | 1 | 37 | 95 | 23 | 9 | ***39%*** | 37% |
| **Armature coil preparation** | 4 | 148 | 130 | 68 | 9 | ***14%*** | 35% |
| **Armature winding** | 5 | 185 | 300 | 37 | 10 | ***26%*** | 32% |
| **Interpole winding** | 3 | 111 | 195 | 34 | 9 | ***27%*** | 42% |
| **Mainpole winding** | 2 | 74 | 130 | 34 | 10 | ***29%*** | 37% |
| **Final assembly** | 6 | 222 | 240 | 56 | 10 | ***18%*** | 38% |
| **Motor Test** | 1 | 37 | 60 | 37 | 10 | ***26%*** | 52% |
| **Motor spray & pack** | 1 | 37 | 40 | 56 | 9 | ***17%*** | 55% |

***Notes:***

- The cycle times are for the average sized motor produced during the study period, frame size ‘200’.
- For the appropriate cells the cycle times were proportionally adjusted upwards to account for the 13% of elevator LDC motors produced in the LDC area during the same period.
- Final assembly cycle time included 60 minutes for the magnet body assembly
- The motor spray cycle times did not include the drying time (as the value added processing times did) just the actual spraying time.

# Appendix 19 – BC Throughput Efficiency Measure

| *Operation* | *Processing times (minutes)* | | | | | |
|---|---|---|---|---|---|---|
| | ***132*** | ***160*** | ***180*** | ***200*** | ***225*** | ***250*** |
| Commutator build | 120 | 120 | 120 | 180 | 180 | 200 |
| Armature assembly | 60 | 60 | 60 | 90 | 120 | 120 |
| Armature winding | 400 | 300 | 300 | 300 | 300 | 330 |
| Armature test | 30 | 30 | 30 | 30 | 30 | 30 |
| Armature soldering & insulating | 40 | 40 | 40 | 40 | 40 | 40 |
| Armature impregnation | 670 | 670 | 670 | 670 | 670 | 670 |
| Armature finishing | 60 | 60 | 60 | 90 | 90 | 90 |
| Final assembly | 120 | 160 | 160 | 160 | 200 | 200 |
| Motor test | 60 | 60 | 60 | 60 | 60 | 60 |
| Spray and ship | 670 | 670 | 670 | 670 | 670 | 670 |
| ***Value added time (minutes)*** | ***2140*** | ***2080*** | ***2080*** | ***2200*** | ***2270*** | ***2320*** |
| ***Value added time (hours)*** | ***35.7*** | ***34.7*** | ***34.7*** | ***36.7*** | ***37.8*** | ***38.7*** |

***Notes:***

- The larger motors (280 and 355 frame size) were excluded from the throughput efficiency measure because they required extra processes, which added 2 weeks to the allowed throughput time. Including these large motors may have skewed the throughput efficiency results, since the larger motors were predominantly manufactured under the ETO approach.

- The processing times were measured over the factory operating hours (37 hours per week) therefore the armature impregnation and motor painting processes each estimated at 1.5 days were equivalent to 11 hours operating time.

- The armature impregnation and motor spraying processing times included the time in the impregnation baths and the paint drying times respectively.

- Neither the armature test or motor test processes were considered to be value added processes therefore their cycle times were not included in the value added time totals

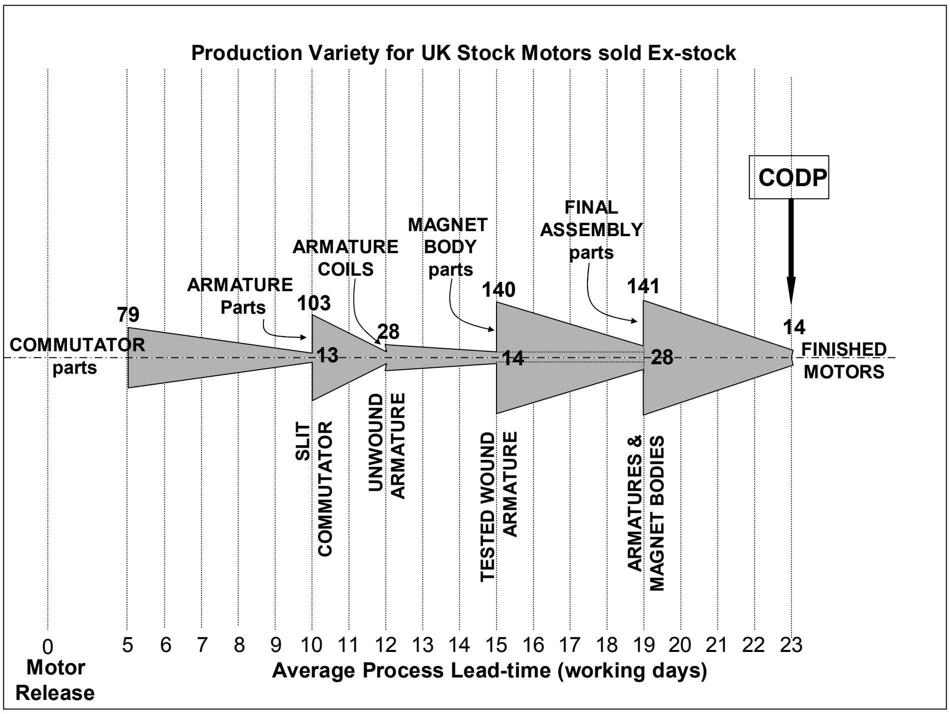
# Appendix 20 – BC Production Variety Funnels

**Part Kits delivered to LDC Manufacture**

| ***Kit name*** | ***Destination Cell*** | ***Parts and codes taken from UK Stock Motor 180S 99040121 JBA BOM*** | ***Leadtime (days)*** |
|---|---|---|---|
| ***Commutator parts from stores*** (BOM level 5) | Commutator | Copper Segments (8), Mica (8), mica vee rings (4) and mica sheet (4) | 1 |
| ***Arm parts from stores*** (BOM level 3) | Armature core build | Arm laminates (8), CE and DE winding carrier rings (8), circlip ext (8) arm keys (8), dowel pin (4) | 2 |
| ***Commutator parts from m/c shop*** (BOM level 5) | Commutator | Commutator sleeve (K ), fixed and free v-rings (K), commutator nut (K) | 5 |
| ***Arm parts from m/c shop*** (BOM level 3) | Armature shafting /assy | Shaft (5), shaft nut (K), CE and DE pressure castings (K), commutator support (K), shaft spacer (K), poss pressure blocks etc | 10 (132-250)<br>15 (280-355) |
| ***Magnet body and final assembly parts from m/c shop*** (BOM level 2) | Final assembly | magnet frame assembly (5), CE and DE bracket (5), tacho adaptor plate (5), caps inner and outer (K). (Only 1st 2 parts for mag body, rest for final assy) | 15 (132-250)<br>20 (280-355) |
| ***Final assy parts from stores*** (BOM level 1) | Final assembly | Numerous parts coded 7 or 8 e.g. roller bearings and covers (8) | |

## Estimation of Commutator Part Variety

| *Part No* | *Part description* | *Material Code #* | *Varies with:* |
|---|---|---|---|
| T031 | Copper Segs | 8 | Frame Size +Length of Brush Area |
| T032 | Mica Segs | 8 | Frame Size +Length of Brush Area |
| T034 | Mica Vee Ring | 4 | Frame Size |
| T034 | Mica Vee Ring | 4 | Frame Size |
| | Mica Sheet | 4 | Frame Size +Length of Brush Area |
| T037 | Free Vee ring | K | Frame Size +Speed |
| T037 | Fixed Vee Ring | K | Frame Size +Speed |
| T035 | Commutator Sleeve | K | Frame Size +Length of Brush Area + Speed |
| T038 | Commutator nut | K | Frame Size |

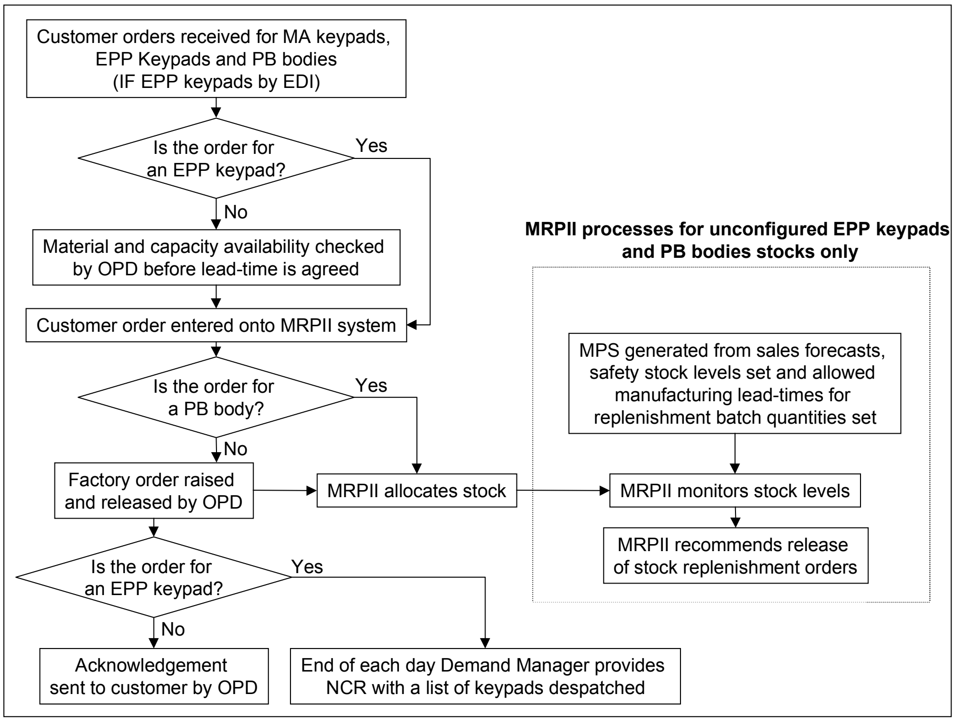


# Appendix 21 – Dewhurst Change Content Data

**Full Process Flow charts for the Keypads**

| Process Description | Symbols | | | |
|---|---|---|---|---|
| **MA Keypads** | | | | |
| Kit of material issued by stores to **w/c 700** | ○ | □ | ➡ | ▽ |
| **Keytips placed in jig** | ● | □ | ⇨ | ▽ |
| **Shims, rubber seal and key locators assembled** | ● | □ | ⇨ | ▽ |
| **C-clip fixed to each key stud to secure keys** | ● | □ | ⇨ | ▽ |
| **Assembly inverted & face plate screwed to front** | ● | □ | ⇨ | ▽ |
| **Earthing tabs, PCB & backplate assembled** | ● | □ | ⇨ | ▽ |
| Keypads mechanically & visually inspected at **w/c 906** | ○ | ■ | ⇨ | ▽ |
| **Keypads packed into individual cartons at w/c 700** | ● | □ | ⇨ | ▽ |
| Keypads book into & out of stores & sent to despatch | ○ | □ | ➡ | ▽ |
| **EPP Keypads** | | | | |
| Kit of material issued by stores to **w/c 702** | ○ | □ | ➡ | ▽ |
| **Keyskirts loaded into keypad casting & resistor fitted** | ● | □ | ⇨ | ▽ |
| **Shim, rubber mat, PCB & metal plate assembled over back of key area** | ● | □ | ⇨ | ▽ |
| **Resistors screwed down & cables clamped** | ● | □ | ⇨ | ▽ |
| Keypads electrically and mechanically tested | ○ | ■ | ⇨ | ▽ |
| **UNCONFIGURED EPP KEYPAD** stored on shopfloor | ○ | □ | ⇨ | ▼ |
| Unconfigured EPP keypads moved to **w/c 711** | ○ | □ | ➡ | ▽ |
| **Glue applied to key skirts** | ● | □ | ⇨ | ▽ |
| **Steel keytip's plastic coating removed** | ● | □ | ⇨ | ▽ |
| **Keytips are located in keyskirts** | ● | □ | ⇨ | ▽ |
| **Plastic keytips laser marked on w/c 712** | ● | □ | ⇨ | ▽ |
| Keypads visually inspected & packed in boxes of 12 | ○ | ■ | ⇨ | ▽ |
| Keypads moved to despatch | ○ | □ | ➡ | ▽ |
| **Operation** | ● | | | |
| **Inspection** | | ■ | | |
| **Transport** | | | ➡ | |
| **Storage** | | | | ▼ |

### Inventory Management (order processing and stock control)




Orders were received for EPP keypads from NCR every morning via EDI, immediately logged on the MAPICS system and the respective factory orders raised and released. In contrast to the receipt of MA keypad and PB body orders, material availability (unconfigured EPP keypads and keytips) and capacity availability were not checked but assumed to be available. With regard to material availability high stocks of the unconfigured keypads were always kept and generally NCR ordered EPP keypads from an established list of finished part numbers. This enabled Dewhurst to ensure that all the keytips featured on these keypads were continually available under a Kanban system. When an order was received for either unusually high quantities or a new EPP keypad item then it appeared on the 12-week rolling forecast (supplied weekly by NCR) and material stocks adjusted accordingly.

It had been agreed with NCR that Dewhurst would deliver all orders submitted by NCR on time and in full when the lead-time given was 5 days or more. The implications for Dewhurst were that the capacity, particularly at the order-driven EPP gluing and populating process, must be very flexible and easily ramped up.

Occasionally NCR changed orders within the agreed 5 day lead-time, these were called either "jump-ons" or "pull forwards". The name related to NCR's reason for making the change but the result was the same for Dewhurst, an additional order was placed on a lead-time shorter than 5 days.

An agreement existed with NCR that separate order acknowledgements were not required, so at the end of each day the Keypad Demand Manager at Dewhurst notified NCR which keypads had been despatched.

The stocks of unconfigured keypad and finished PB bodies were controlled by MAPICS, the MRPII system. MAPICS monitored the stock levels and recommended release of stock replenishment orders on the basis of the Master Production Schedule (MPS), safety stock levels and the allowed manufacturing lead-time.

A number of forecasts were received from NCR but only the 12-week forecast was used to generate the MPS which was effectively the forecasted weekly demand for the three unconfigured EPP keypad variants. The safety stock levels for the unconfigured EPP keypads were set at 2 weeks cover on the basis of NCR's anticipated demand of 3000 keypads per week, however this level of demand did not materialise. Over the 4 month period of the study (1st October '02 to 31st January '03) the average weekly demand was just over half the anticipated level at 1680 keypads. As the charts in Appendix 21 show the stock levels were around 3000 unconfigured keypads for the first 2 months of the study and then rapidly increased to around 6000 keypads. Unfortunately the demand did not increase therefore stock levels rose to around 3.5 weeks cover substantially more than the target of 2 weeks.

The MPS for the ten PB body variants was more complicated to generate because the bodies were subject to both dependant demand (as in the case of the unconfigured EPP keypads) and independent demand from numerous customers. The Planning Manager used historical data, information from the sales department and statistics to generate MPS. The safety stock levels varied, depending on the historical demand, ranging between zero for two variants up to 2000 for the standard variant. However, quite often the actual stock levels were five times, or more, their target level. Further, although the standard variant was clearly subject to the greatest demand over the period of the study accounting for 80% of demand, the safety stock provision for the remaining variants generally did not reflect demand. In fact the average weekly stock cover over the study period varied between 6 weeks for the standard variant to 380 weeks for the variant subject to the lowest demand. This may have been because the study only analysed the independent demand on the PB bodies and not the dependant demand generated when the bodies were sold as a fully assembled pushbutton.

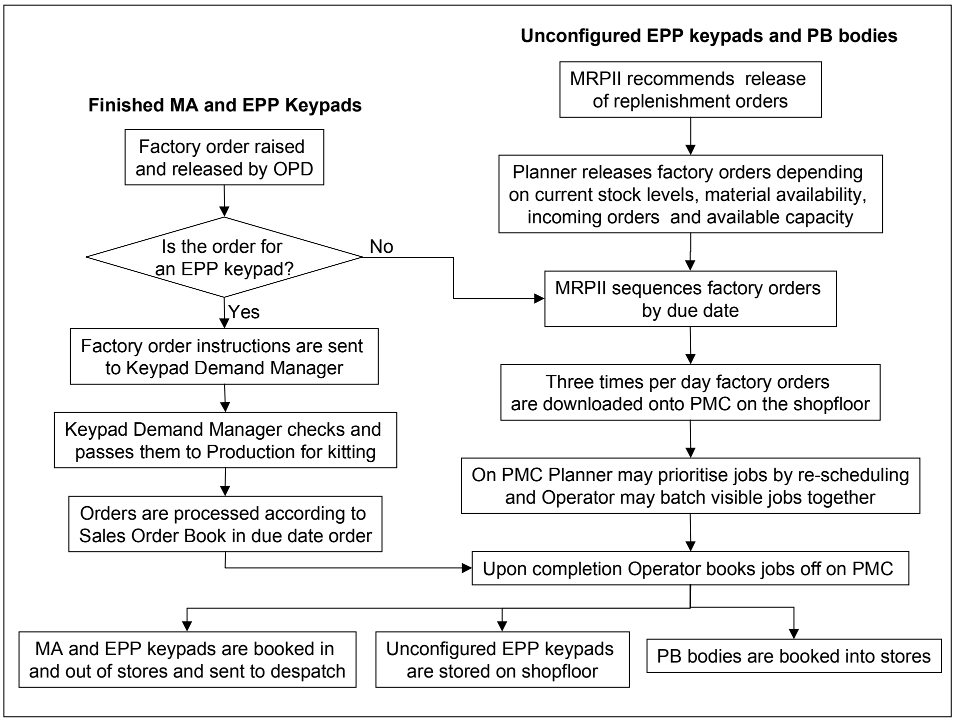
The stock replenishment batch quantity for the unconfigured EPP keypads was variable and set by the Planners depending on unconfigured keypad stock levels, components availability and capacity availability. The allowed manufacturing lead-time was always 5 days.

The stock replenishment batch quantity for the standard PB body was 10,000 and the allowed manufacturing lead-time for PB bodies was always 10 days. For the standard PB body variant 10 days was a realistic lead-time since PB bodies were produced at a rate of 50 per man-hour over a 37.5 hour week when only 4 people were likely to work on the job at any one time. The other nine variants were manufactured in much smaller and variable batch quantities for which 10 days lead-time was excessive.

The keytips stocks were controlled by various Kanban systems from a 20-bin Kanban system for the highest volume grey plastic keytips to a re-order point card system for the lowest volume MA keytips. All MA keytips were on the re-order point card system except for those destined for the main customer Fujitsu which were on a 2-bin Kanban system to generate more stock. For EPP keytips the volume demand, which dictated the

Kanban system used, depended on their material and their location on the keypad. Plastic keytips were demanded in higher volume than steel and numeric keytips were demanded in higher volume than side keytips. The plastic, numeric (standard grey) keytips were on a 20 bin Kanban system, the plastic side keys and steel numeric keytips were on either a 2 or 3 bin system and the steel side keys were on a ticket system.

**Manufacturing Planning and Scheduling**




Factory orders for order driven production of the finished MA and EPP keypads were raised by OPD and automatically released. Prior to this, in the case of MA keypads, OPD checked material and capacity availability to ensure the lead-time could be met, however both material and production capacity were assumed to be available for the configuration of the EPP keypads.

Crucially no stock replenishment factory orders were automatically released instead the MRP system made recommendations and the Planning Manager released the orders. The Planning Manager scrutinised the recommendations once each week and decided which orders to release on the basis of the current stock levels, material availability, incoming orders and available capacity. Although the MPS and the set safety stock levels are supposed to drive these stocks ultimately the Planning Manager controlled both the timing and quantity of the replenishment orders.

Available capacity was determined by using a Work Centre Load Analysis generated by MAPICS. This calculated the load hours based on the quantity planned to be produced and the cycle times and subtracted this from the available capacity to give available capacity. The Planning Manager monitored the current work centre overload on a weekly basis and only intervened when there was a significant change in the overload. Effectively production planning assumed an infinite capacity was available. The labour driven processes, particularly the EPP keypad assembly processes, were viewed as unlikely bottle necks. This was because the skill level required for these assembly operations was very low and therefore the opportunity always existed to employ temporary staff to boost capacity.

With regards to scheduling released manufacturing orders were downloaded three times each day from MAPICS to the PMC system, with the exception of finished EPP keypad orders which are discussed below. This ensured on average a delay of 4 hours, and in the worst case a delay of 8 hours, between the order being released by OPD and being available on PMC for manufacturing. PMC was a shopfloor computerised system which provided each work centre with a “load sheet” listing jobs in due date order. The Operators were able to view the load sheet and normally processed the jobs in the sequence recommended with three exceptions.

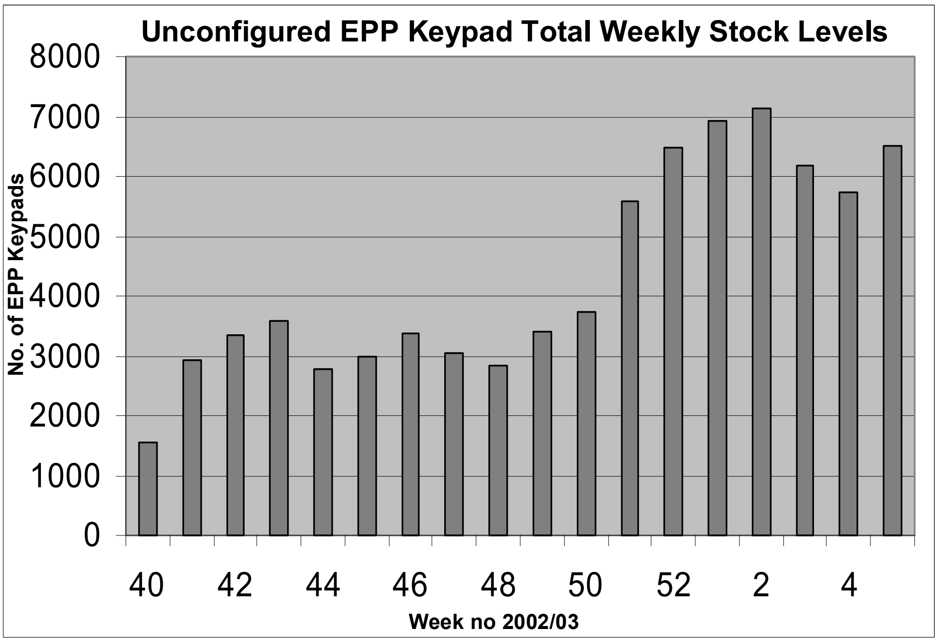
Firstly if material was not available the job was missed. Secondly, the Planner occasionally resequenced the orders to reprioritise urgent orders. Thirdly if the opportunity existed similar jobs were batched together. However, particularly on the products in this study, this was a very rare event because PB body and unconfigured EPP keypad stock replenishment orders were effectively already batched together and the finished EPP keypad orders had been batched (if the opportunity existed given their high variety) by NCR. MA keypads were subjected to few repeat orders, therefore it’s highly unlikely that two orders for the same specification would be due in the same time period.

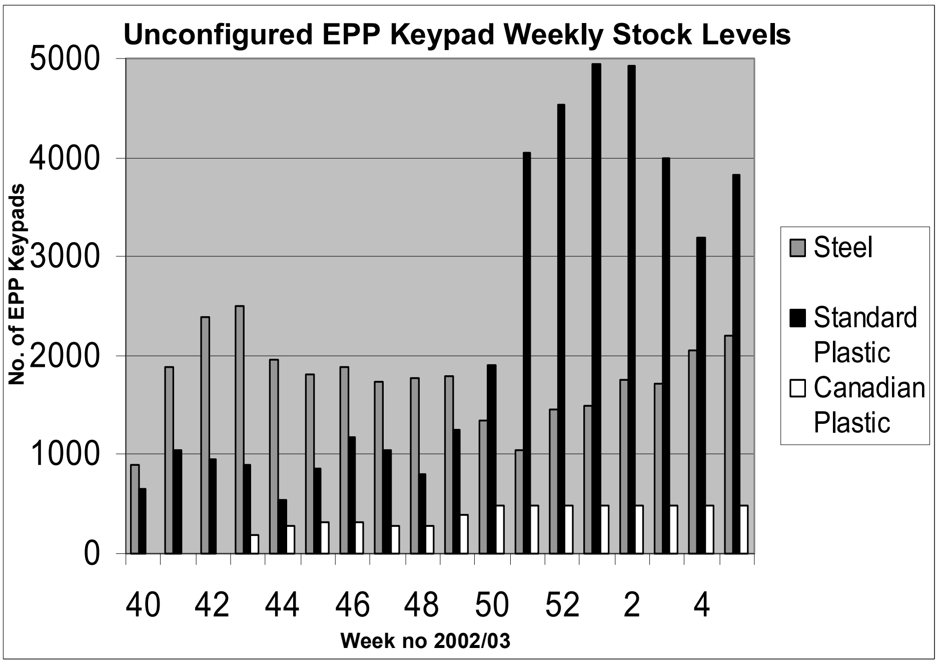
Returning to the finished EPP keypad manufacturing orders, once released by the Order Processing Department they by-passed the PMC system to ensure a rapid response from production. Hard copies of the EPP manufacturing orders were passed to the Keypad Demand Manager checked and delivered to Production typically by 10.30am, only 1.5 hours after the customer orders were sent via EDI to Dewhurst. Once in production the EPP orders were immediately kitted and then processed in due date order according to the Sales Order Book.

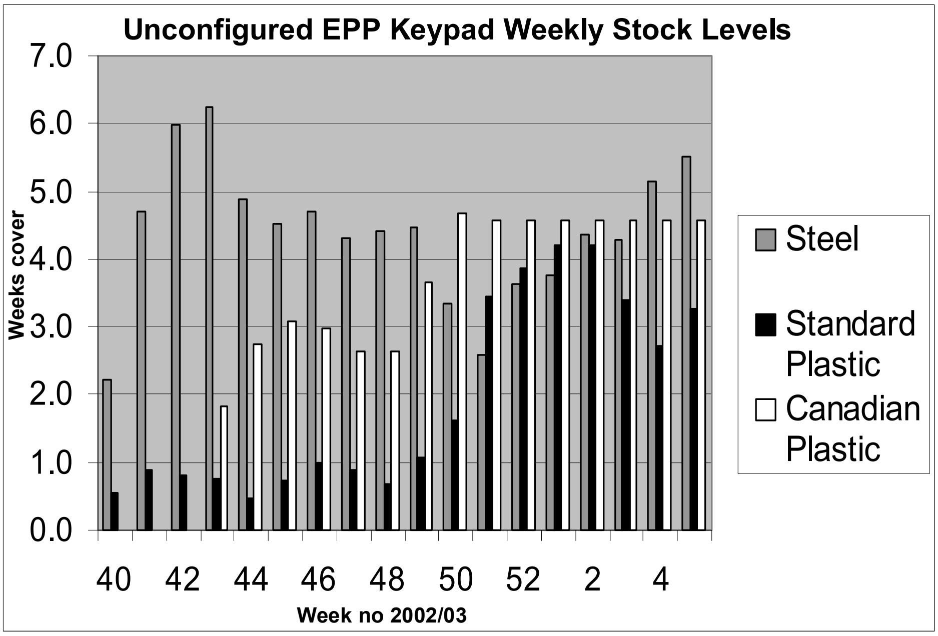
To summarise in general the manufacturing planning and scheduling system at Dewhurst is a very responsive one. The MRP system is run on a nightly basis and released manufacturing orders are downloaded 3 times each day to PMC which automatically schedules jobs in due date order. Therefore in the worst case a manufacturing order experienced an 8 hour delay between being released and being available for manufacture on PMC. Nevertheless the finished EPP keypad manufacturing orders were given special treatment and by-passed the PMC system to ensure a rapid response from production. Typically only 1 hour passed between the EPP manufacturing orders being released and being available for manufacture.

**Stock Records for Unconfigured EPP Keypads and PB Bodies**

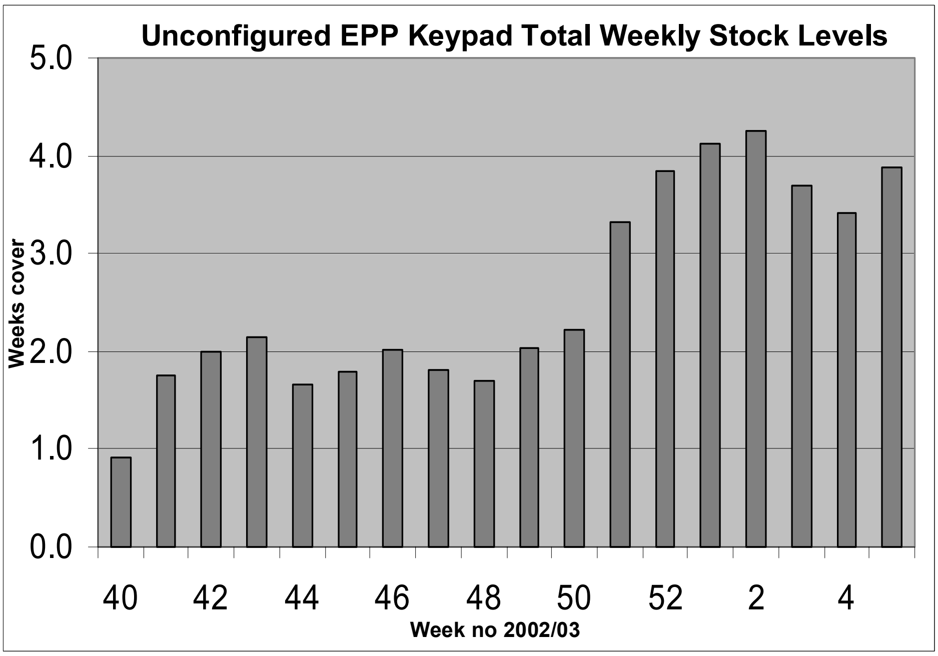
***Note:*** The zero stock level recorded for the Canadian plastic keypads over the first few weeks was before they were made available.



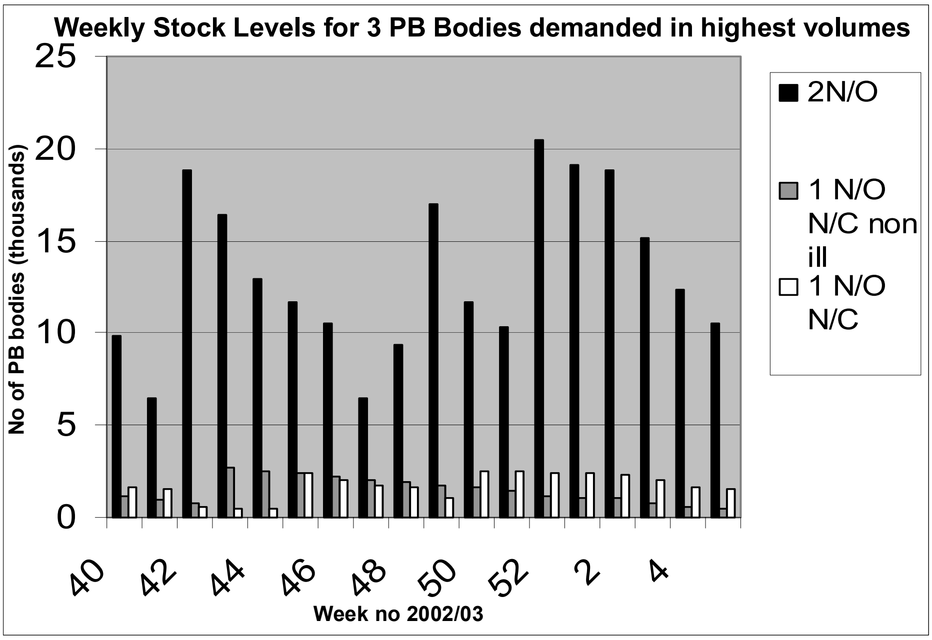



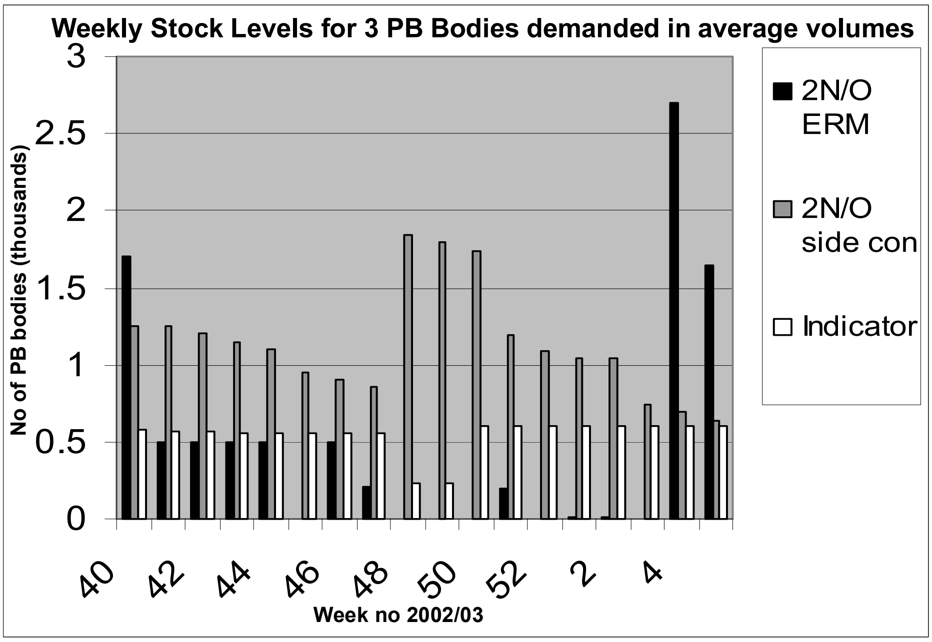


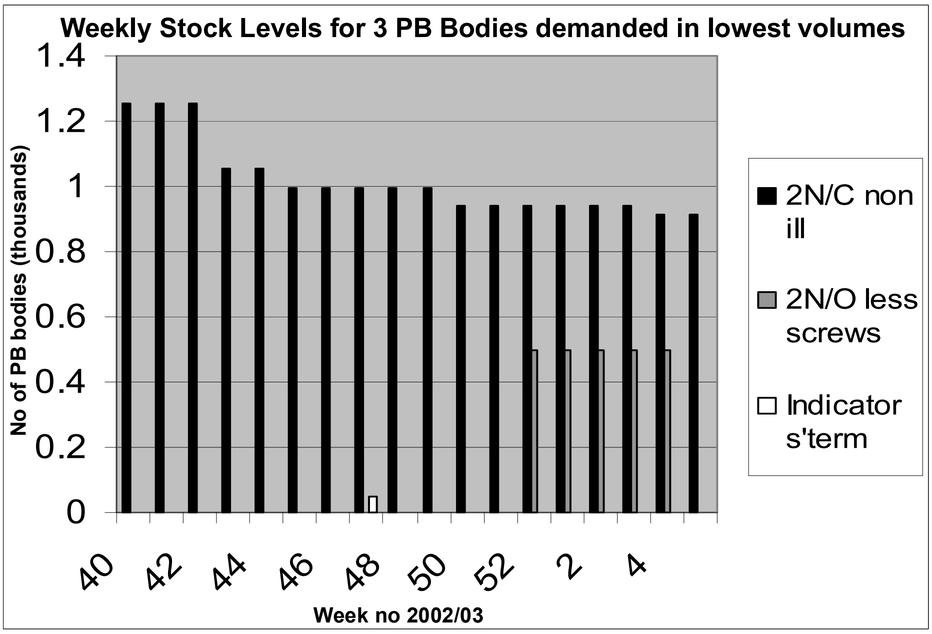
Unconfigured EPP Keypad Weekly Stock Levels
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Weeks cover
Steel
Standard Plastic
Canadian Plastic
40
42
44
46
48
50
52
2
4
Week no 2002/03

Unconfigured EPP Keypad Total Weekly Stock Levels
5.0
4.0
3.0
2.0
1.0
0.0
Weeks cover
40
42
44
46
48
50
52
2
4
Week no 2002/03


Weekly Stock Levels for 3 PB Bodies demanded in highest volumes
No of PB bodies (thousands)
0
5
10
15
20
25
40
42
44
46
48
50
52
2
4
Week no 2002/03
2N/O
1 N/O N/C non ill
1 N/O N/C


Weekly Stock Levels for 3 PB Bodies demanded in average volumes
No of PB bodies (thousands)
0
0.5
1
1.5
2
2.5
3
40
42
44
46
48
50
52
2
4
Week no 2002/03
2N/O ERM
2N/O side con
Indicator


Weekly Stock Levels for 3 PB Bodies demanded in lowest volumes
No of PB bodies (thousands)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
40
42
44
46
48
50
52
2
4
Week no 2002/03
2N/C non ill
2N/O less screws
Indicator s'term

# Appendix 22 – Dewhurst Manufacturing Data

The operating hours for the Dewhurst factory were 37.5 hours per week. Below are details of the production arrangements, labour levels, unit processing times and cycle times for the EPP keypads, MA keypads and PB bodies, where:

- unit processing time is measured in man minutes and is the time required to complete the assembly process on 1 unit.

- cycle time is measured in minutes and is the time period between units being completed on a production cell.

The cycle times were calculated from a knowledge of the production arrangement (i.e. production lines or individual work stations) and the unit processing times. Where only one man is involved in the assembly of each unit (i.e. an individual work station) processing and cycle times are the same. However where more than one man was involved in the assembly of each unit (i.e. a production line) then the cycle time is less than the processing time by a factor of the number of people on the line.

**EPP Keypad**

- Between 1st October and 20th December the unit processing times for the assembly of the EPP keypad depended on whether the belt line was used. According to Flow Process Charts recorded by Production if the belt line was used the processing time was 8.5 man minutes, however if it wasn't used the processing time was 5.5 man minutes. The keypad assembly processing times in the table below are adjusted according to the number of belt lines used.

- Initially the configuring of the keypads was conducted by work stations where a single person conducted all operations manually. After 18th November a gluing machine was commissioned and a configuring line was established requiring 3 people. However, this did not reduce the processing times but did reduce the cycle time by a factor of 3, the number of people on the line. The keypad configuring cycle times in the table below are adjusted according to the number of gluing stations versus gluing lines.

- For both the keypad assembly and the keypad configuration process cycle times dropped over the study period. In the case of keypad assembly this was due to the gradual change to non-belt assembly lines and in the case of keypad configuration it was due to the gradual change from individual "gluing" stations to "gluing" lines. However, in both cases the elapsed time, or manufacturing lead-times, remained about the same. Therefore the trend was for throughput efficiency to drop over the study period.

The table below summarises the changes in the EPP production arrangement and the resulting labour levels and cycle times over the period of the study.

| | 1st - 4th Oct | 7th Oct - 15th Nov | 18th Nov – 20th Dec | 6th - 17th Jan | 20th - 31st Jan |
|---|---|---|---|---|---|
| ***Production Arrangement*** | | | | | |
| ***Keypad Assembly*** | 1 belt line of 3 people and 1 non-belt line | 2 belt lines of 3 people and 1 non-belt line | 2 belt lines of 3 people and 1 non-belt line | 2 non-belt lines of 3 people | 1 non-belt lines of 3 people |
| ***Configuring Keypad*** | Up to 6 “gluing” stations | Up to 6 “gluing” stations | 1 “gluing” line of 3 people with up to 2 “gluing” stations | 1 “gluing” line of 3 people | 1 “gluing” line of 3 people |
| ***Labour levels*** | | | | | |
| ***Keypad Assembly*** | 6 | 9 | 9 | 6 | 3 |
| ***Configuring Keypad*** | 6 | 6 | 5 | 3 | 3 |
| ***Unit Processing Times (man minutes)*** | | | | | |
| ***Keypad Assembly*** | 7 | 7.5 | 7.5 | 5.5 | 4.5 |
| ***Configuring Keypad*** | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| ***Cycle Times (minutes)*** | | | | | |
| ***Keypad Assembly*** | 2.3 | 2.5 | 2.5 | 1.8 | 1.5 |
| ***Configuring Keypad*** | 4.5 | 4.5 | 2.7 | 1.5 | 1.5 |

## MA Keypads

The labour level for the MA keypad cell remained at 2 people throughout the study period, however production was always arranged so that only one man would assemble each unit. Therefore the unit processing times and cycle times are the same. Also all MA keypads required a 30 minute setup time. The table below provides the cycle times required for the 6 MA keypad types.

| ***MA Keypad*** | ***Processing and Cycle Time (man minutes)*** |
|---|---|
| MA11 (4x4 keys) | 15.5 |
| MA10 (4x3 keys) | 14 |
| MA12 (4x1 keys) | 10.5 |
| Fujitsu 1038 (4x4 keys) | 20 |
| Fujitsu 1039 (4x1 keys v1) | 6 |
| Fujitsu 1040 (4x1 keys v2) | 6 |

**PB Bodies**

The assembly of the switch bodies was normally performed by a production line of 2 men therefore the cycle time is half the processing time. The Assembly of all PB bodies required a 15 minute setup time. The table below provides the times required for the 2 types of PB bodies

| ***PB body*** | ***Assembly Processing Time (man minutes)*** | ***Assembly Cycle Time (minutes)*** |
|---|---|---|
| PB switch | 1.2 (50/man hour) | 0.6 (100/hour) |
| PB indicator | 0.5 (120/man hour) | 0.5 (120/hour) |

# Appendix 23 – Dewhurst Demand Measures

**The demand measures for the FPp unit of analysis (EPP Keypads) for orders due between 1st October '02 and 31st January '03**

| *EPP Type* | *Item No.* | *Weekly Demand* | | | *Totals* | |
|---|---|---|---|---|---|---|
| | | *Avg* | *SD* | *CV (%)* | *Demand* | *Orders* |
| *Plastic EPP* | 004450-660001 | 10 | 25 | 245 | 165 | 7 |
| | 004450-660002 | 48 | 96 | 201 | 764 | 8 |
| | 004450-660003 | 26 | 60 | 235 | 412 | 8 |
| | 004450-660008 | 1 | 3 | 400 | 12 | 1 |
| | 004450-660010 | 8 | 15 | 192 | 125 | 9 |
| | 004450-660013 | 2 | 5 | 202 | 38 | 4 |
| | 004450-660014 | 694 | 536 | 77 | 11108 | 36 |
| | 004450-660015 | 41 | 40 | 98 | 661 | 23 |
| | 004450-660017 | 5 | 9 | 190 | 73 | 6 |
| | 004450-660018 | 1 | 3 | 400 | 12 | 1 |
| | 004450-660019 | 26 | 46 | 181 | 408 | 15 |
| | 004450-660020 | 3 | 7 | 231 | 48 | 3 |
| | 004450-660026 | 1 | 3 | 400 | 12 | 1 |
| | 004450-660030 | 6 | 12 | 193 | 96 | 6 |
| | 004450-660031 | 8 | 14 | 181 | 122 | 6 |
| | 004450-660032 | 110 | 102 | 92 | 1763 | 39 |
| | 004450-660033 | 2 | 4 | 274 | 26 | 2 |
| | 004450-660034 | 2 | 5 | 208 | 37 | 4 |
| | 004450-660035 | 1 | 3 | 368 | 13 | 2 |
| | 004450-660038 | 2 | 4 | 273 | 24 | 2 |
| | 004450-660040 | 2 | 5 | 208 | 37 | 4 |
| | 004450-660042 | 0 | 0 | 400 | 1 | 1 |
| | 004450-660043 | 3 | 7 | 260 | 40 | 3 |
| | 004450-660047 | 2 | 4 | 273 | 24 | 2 |
| | 004450-660048 | 1 | 3 | 400 | 12 | 1 |
| | 004450-660051 | 19 | 35 | 184 | 303 | 19 |
| | 004450-660055 | 6 | 15 | 240 | 100 | 6 |
| | 004450-660056 | 1 | 3 | 400 | 10 | 1 |
| | 004450-660058 | 1 | 3 | 400 | 12 | 1 |
| | 004450-660059 | 1 | 3 | 344 | 14 | 3 |
| | 004450-660076 | 142 | 285 | 201 | 2297 | 21 |
| ***Sub-totals*** | ***31 end items*** | ***1172*** | ***686*** | ***59*** | ***18769*** | ***245*** |

| EPP Type | Item No. | Weekly Demand | | | Totals | |
|---|---|---|---|---|---|---|
| | | Avg | SD | CV (%) | Demand | Orders |
| Canadian Plastic EPP | 004450-660016 | 1 | 3 | 247 | 21 | 5 |
| | 004450-660072 | 102 | 212 | 208 | 1637 | 9 |
| | 004450-660073 | 1 | 3 | 400 | 12 | 1 |
| | 004450-660074 | 2 | 9 | 400 | 37 | 2 |
| ***Sub-totals*** | ***4 end items*** | ***107*** | ***211*** | ***198*** | ***1707*** | ***17*** |
| Steel EPP | 004450-660103 | 1 | 2 | 400 | 9 | 1 |
| | 004450-660104 | 12 | 36 | 295 | 193 | 6 |
| | 004450-660105 | 24 | 42 | 175 | 385 | 12 |
| | 004450-660107 | 8 | 12 | 146 | 132 | 11 |
| | 004450-660108 | 0 | 1 | 400 | 5 | 1 |
| | 004450-660110 | 46 | 27 | 59 | 734 | 38 |
| | 004450-660112 | 27 | 63 | 229 | 438 | 11 |
| | 004450-660113 | 5 | 7 | 165 | 72 | 5 |
| | 004450-660114 | 1 | 3 | 400 | 12 | 1 |
| | 004450-660115 | 61 | 38 | 62 | 983 | 55 |
| | 004450-660118 | 4 | 6 | 135 | 67 | 7 |
| | 004450-660120 | 0 | 2 | 400 | 6 | 1 |
| | 004450-660121 | 1 | 2 | 253 | 11 | 3 |
| | 004450-660122 | 5 | 11 | 209 | 81 | 5 |
| | 004450-660123 | 2 | 5 | 281 | 31 | 3 |
| | 004450-660124 | 3 | 7 | 231 | 48 | 3 |
| | 004450-660125 | 2 | 9 | 400 | 36 | 1 |
| | 004450-660126 | 48 | 39 | 82 | 761 | 37 |
| | 004450-660128 | 35 | 46 | 134 | 553 | 12 |
| | 004450-660129 | 2 | 6 | 289 | 35 | 4 |
| | 004450-660131 | 3 | 5 | 190 | 40 | 6 |
| | 004450-660132 | 11 | 18 | 173 | 169 | 17 |
| | 004450-660133 | 1 | 4 | 332 | 17 | 3 |
| | 004450-660134 | 17 | 22 | 127 | 276 | 13 |
| | 004450-660135 | 3 | 5 | 174 | 49 | 5 |
| | 004450-660136 | 15 | 15 | 104 | 236 | 14 |
| | 004450-660137 | 9 | 9 | 110 | 136 | 11 |
| | 004450-660138 | 4 | 8 | 221 | 60 | 6 |
| | 004450-660140 | 5 | 12 | 245 | 80 | 7 |
| | 004450-660144 | 1 | 3 | 400 | 12 | 1 |
| | 004450-660146 | 9 | 10 | 115 | 137 | 9 |
| | 004450-660148 | 2 | 4 | 210 | 34 | 4 |
| | 004450-660149 | 8 | 20 | 260 | 120 | 5 |
| | 004450-660158 | 27 | 34 | 124 | 432 | 15 |
| | 004450-660159 | 0 | 1 | 400 | 3 | 1 |

| EPP Type | Item No. | Weekly Demand | | | Totals | |
|---|---|---|---|---|---|---|
| | | Avg | SD | CV (%) | Demand | Orders |
| Steel EPP | 004450-660161 | 1 | 2 | 400 | 9 | 1 |
| | 004450-660171 | 1 | 3 | 400 | 12 | 1 |
| ***Sub-totals*** | ***37 end items*** | ***401*** | ***123*** | ***31*** | ***6414*** | ***336*** |
| | | | | | | |
| ***Totals*** | ***72 end items*** | ***1679*** | ***806*** | ***48*** | ***26890*** | ***598*** |
| ***Average per end item (EPP spec)*** | | ***23*** | ***29*** | ***249*** | ***373*** | ***8*** |

**The demand measures for the MTO unit of analysis (MA keypads) for orders due between 1st October '02 and 31st January '03**

| MA Type | Item No. | Description | Weekly Demand | | | Totals | |
|---|---|---|---|---|---|---|---|
| | | | Av | SD | CV (%) | Demand | Order |
| MA10 Keypad | 008100-105000 | STANDARD | 1 | 2 | 168 | 20 | 6 |
| | 008100-105300 | NUMERIC 2 KEY | 1 | 5 | 392 | 21 | 2 |
| | 008100-105095 | FUJITEC SPECIAL | 0 | 1 | 355 | 7 | 2 |
| | 008100-106000 | GDX CONCIERGE | 0 | 1 | 412 | 5 | 1 |
| | 008100-106100 | GDX SERVICE | 0 | 0 | 412 | 2 | 1 |
| | 008100-106700 | BM ELECTRONICS | 1 | 2 | 412 | 10 | 1 |
| | 008100-109500 | IN PANTONE 193C | 8 | 32 | 412 | 130 | 1 |
| ***Sub-total*** | | ***7 end items*** | ***11*** | ***32*** | ***281*** | ***195*** | ***14*** |
| MA11 Keypad | 008110-103400 | 0 TO 9 | 1 | 2 | 412 | 10 | 1 |
| | 008110-103700 | ENGLISH ATM | 0 | 1 | 412 | 5 | 1 |
| | 008110-103800 | FUNCTION *CE | 1 | 2 | 412 | 10 | 1 |
| | 008110-103900 | C&K STANDARD | 0 | 1 | 282 | 4 | 2 |
| | 008110-104500 | NATECH ATM | 0 | 1 | 412 | 5 | 1 |
| | 008110-105700 | NATECH PRISM | 35 | 84 | 239 | 600 | 3 |
| | 008110-106000 | ISM TRADE | 2 | 7 | 282 | 40 | 2 |
| | 008110-107000 | SCHINDLER G B | 0 | 0 | 412 | 1 | 1 |
| | 008110-107600 | ENGLISH ATM *#DOT | 0 | 1 | 412 | 5 | 1 |
| | 008110-108200 | DIGITAL A | 0 | 1 | 412 | 5 | 1 |
| | 008110-108400 | STANDARD | 0 | 1 | 412 | 4 | 1 |
| | 008110-108600 | SM10L06500011 | 1 | 3 | 282 | 20 | 2 |
| | 008110-110000 | 1TO9,STOP,GOED | 6 | 17 | 282 | 100 | 2 |
| | 008110-110400 | SCANCOIN 017893 | 3 | 12 | 412 | 50 | 1 |
| | 008110-103095 | IN2TEC LTD SPECIAL | 1 | 4 | 412 | 15 | 1 |

| *MA Type* | *Item No.* | *Description* | *Weekly Demand* | | | *Totals* | |
|---|---|---|---|---|---|---|---|
| | | | *Av* | *SD* | *CV (%)* | *Demand* | *Order* |
| ***MA11 Keypad*** | 008110-103095 | ALBERTA SPECIAL | 0 | 0 | 412 | 1 | 1 |
| | 008110-103095 | SCHINDLER SPEC. | 0 | 0 | 412 | 1 | 1 |
| | 008110-103095 | BPT SPECIAL | 1 | 4 | 412 | 15 | 1 |
| | 008110-103095 | HITACHI SPECIAL | 0 | 0 | 412 | 1 | 1 |
| Sub-total | | 19 end items | 52 | 82 | 155 | 892 | 25 |
| | | | | | | | |
| ***MA12 Keypad*** | 008120-103999 | SPECIAL | 0 | 1 | 412 | 6 | 1 |
| | | | | | | | |
| ***Fujitsu 4x4*** | 001038-500200 | FUJITSU SPECIAL | 1 | 2 | 295 | 14 | 2 |
| | 001038-501000 | FUJITSU SPECIAL | 2 | 8 | 412 | 32 | 1 |
| ***Sub-total*** | | 2 end items | 2 | 10 | 353 | 46 | 3 |
| | | | | | | | |
| ***Fujitsu 1x4 v2*** | 001040-520200 | FUJITSU SPECIAL | 1 | 2 | 412 | 10 | 1 |
| | | | | | | | |
| ***Fujitsu 1x4 v1*** | 001039-510200 | FUJITSU SPECIAL | 0 | 1 | 412 | 5 | 1 |
| | | | | | | | |
| ***Totals for MA keypads*** | | | ***68*** | ***129*** | ***190*** | ***1154*** | ***45*** |
| ***Average for MA keypad end item*** | | | ***2*** | ***7*** | ***376*** | ***37*** | ***1.5*** |

**MA keypad Demand Mix Discussion**

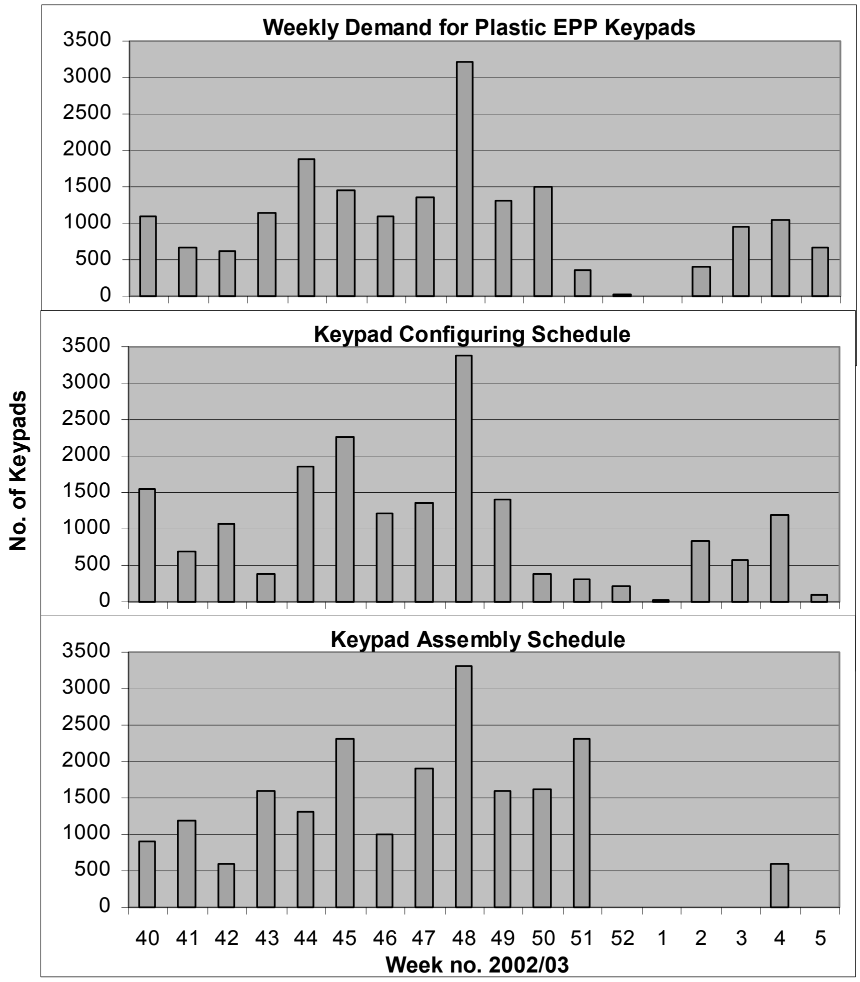
Only 31 variants of the MA keypads were demanded, less than half the demand mix for EPP keypads. The product design analysis suggested that the potential variety was, if anything, greater for the MA than for the EPP keypads. It appears that the low variety in the MA keypads was due to the very low volumes in which they were demanded over the study period. This explanation was supported by the fact that the EPP keypads were demanded in 23 times the volume of the MA keypads yet the number of EPP variants was only 2.3 times the MA keypad variants. On this basis had the MA keypads been demanded in triple the volume (still far lower than the EPP keypad demand volume) the number of finished MA keypad variants would have been significantly greater than for the EPP variants.

**The demand measures for the MTS unit of analysis (pushbutton bodies) for orders due between 1st October '02 and 31st January '03**

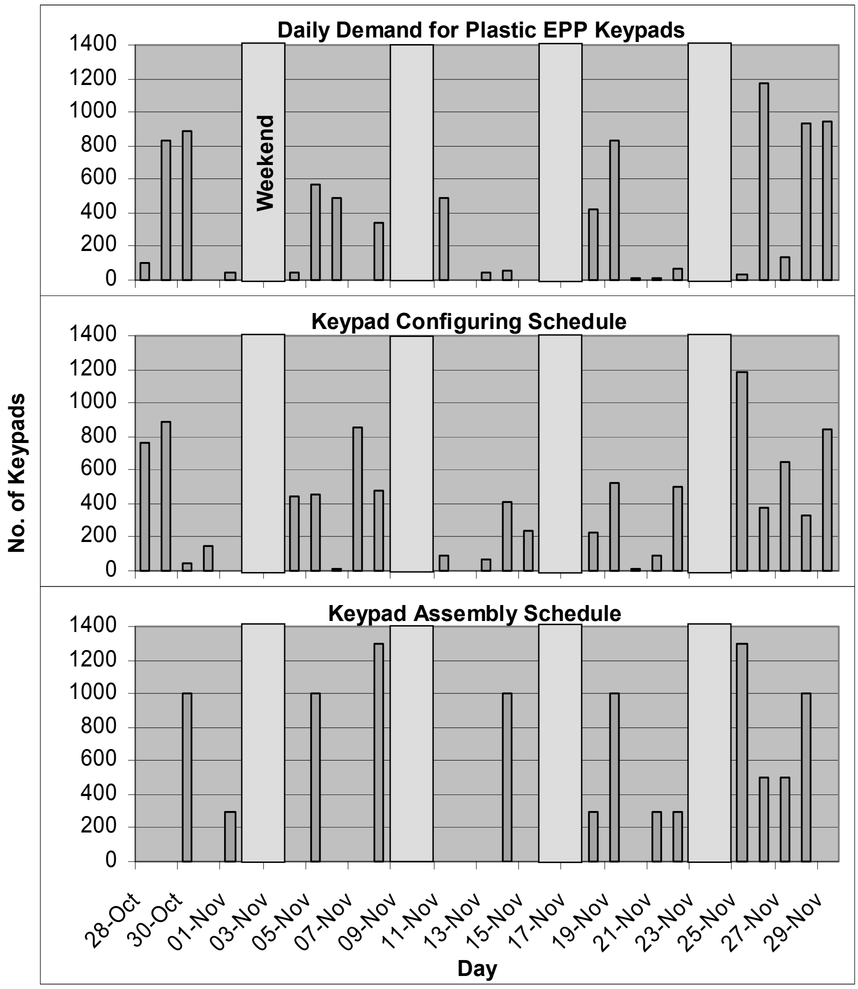
| *Item No.* | *Description* | *Weekly Demand* | | | *Totals* | |
|---|---|---|---|---|---|---|
| | | *Avg* | *SD* | *CV (%)* | *Demand* | *Orders* |
| 004042-300001 | 2N/O | 2,062 | 1127 | 55 | 35,050 | 30 |
| 004042-510001 | 1NO/NC NON ILL | 168 | 50 | 30 | 2,850 | 19 |
| 004042-500001 | 1NO/NC | 120 | 186 | 156 | 2,035 | 9 |
| 004042-300004 | 2N/O SCREW TERM (ERM) | 65 | 203 | 314 | 1100 | 2 |
| 004042-300010 | 2N/O SIDE CONN | 56 | 17 | 30 | 950 | 19 |
| 004042-900001 | INDICATOR BODY | 53 | 159 | 300 | 900 | 2 |
| 004042-410001 | 2N/C NON ILL | 35 | 75 | 215 | 590 | 5 |
| 004042-300005 | 2N/O S' TERM L'SCREW (ERM) | 29 | 121 | 412 | 500 | 1 |
| 004042-900002 | IND BODY SCREW TERM | 3 | 12 | 412 | 50 | 1 |
| 004042-400001 | 2N/C | 1 | 2 | 412 | 10 | 1 |
| ***Totals*** | | ***2,590*** | ***1,172*** | ***45*** | ***44,035*** | ***89*** |
| ***Average per end item (pushbutton body)*** | | ***259*** | ***195*** | ***233*** | ***4,404*** | ***9*** |

# Appendix 24 – Dewhurst Demand Amplification Charts

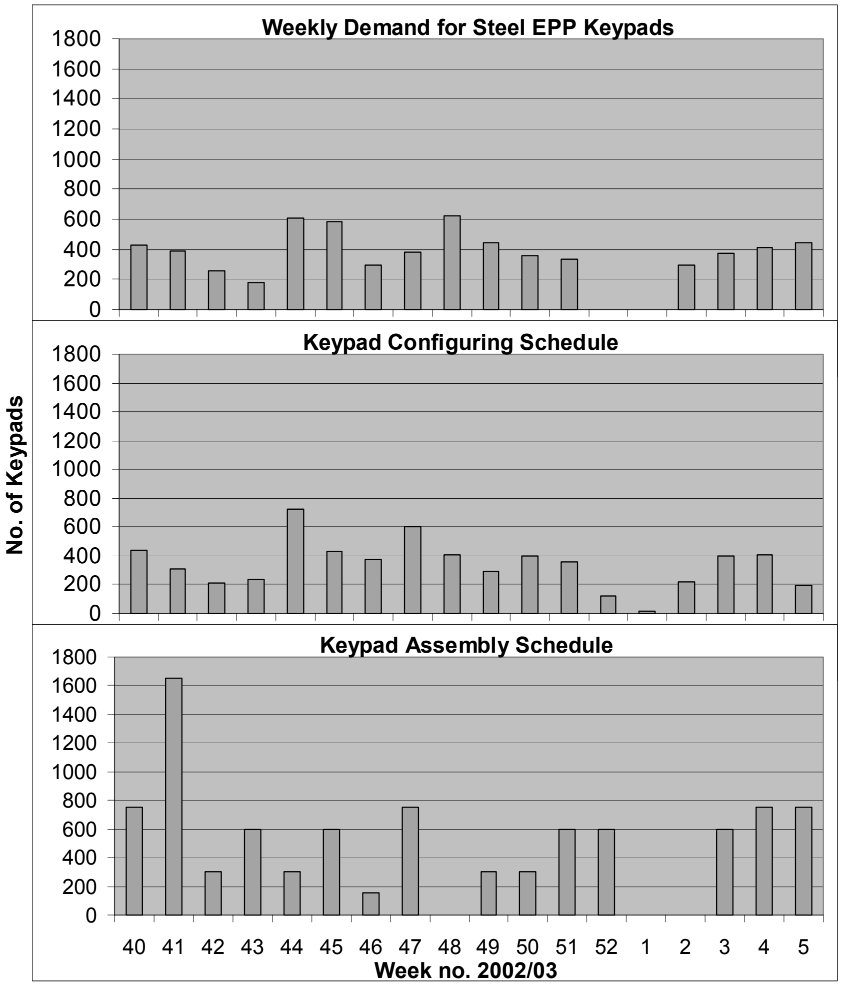
## Demand Amplification measured at a weekly level for plastic EPP keypads due between 30th September '02 and 31st January '03



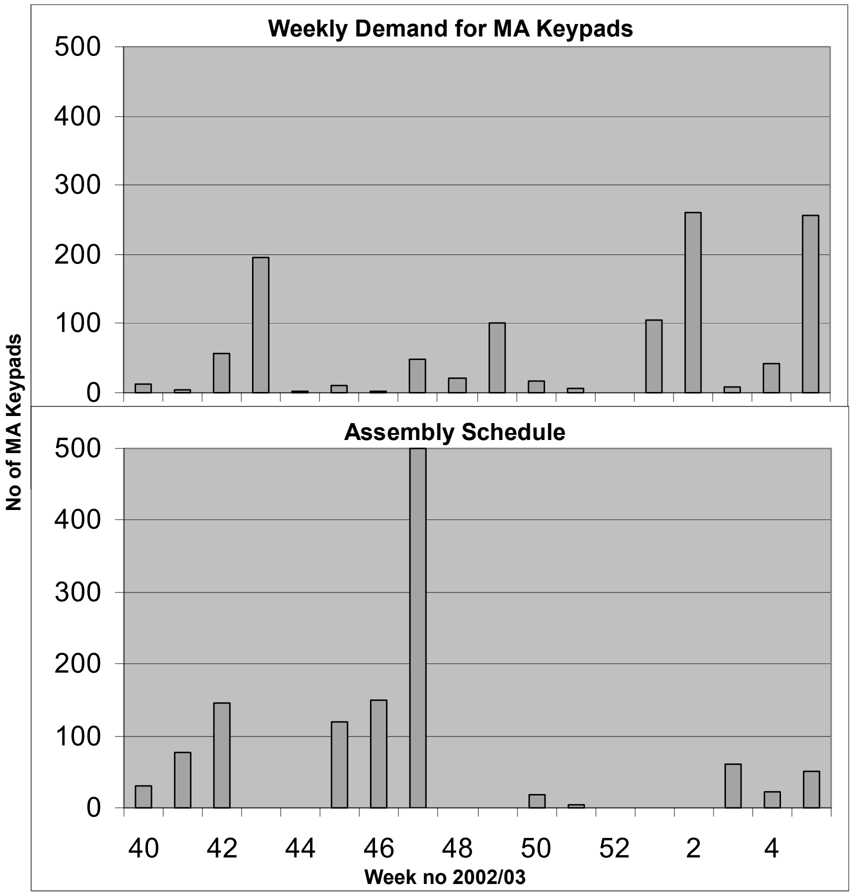
# Demand Amplification measured at a daily level for plastic EPP keypads due between 28th October and 29th November '02



# Demand Amplification measured at a weekly level for steel EPP keypads due between 30th September '02 and 31st January '03



# Demand Amplification for MA Keypads due Between 1st October '02 and 31st January '03




**MA Keypad Demand Amplification Chart**

The demand amplification chart for the MA keypads shows weekly demand for the keypads and the assembly schedule. Generally the peaks in the assembly schedule are of a similar amplitude to the peaks in demand except for one very large peak of 500 keypads scheduled to start in week 47. Upon investigation it was found that this was made up of two manufacturing orders each for 250 keypads which were due for delivery in January 2003. Both orders were for the same keypad specification destined for the same customer and their manufacture had effectively been batched together. With the exception of this incidence of batching there is no evidence of demand amplification for the MA keypads.

# Appendix 25 – Dewhurst BOM Analysis Parts

## The parts for the FPp unit of analysis (EPP Keypads)

| BOM Level | Item Description | Part Type | Generic Item No. |
|---|---|---|---|
| Level 1 | Keytip 1 | Essential | 001077 |
| | Keytip2 | Essential | 001077 |
| | Keytip 3 | Essential | 001077 |
| | Function Keytip | Essential | 001077 |
| | Keytip 4 | Essential | 001077 |
| | Keytip 5 | Essential | 001077 |
| | Keytip 6 | Essential | 001077 |
| | Function Keytip | Essential | 001077 |
| | Keytip 7 | Essential | 001077 |
| | Keytip 8 | Essential | 001077 |
| | Keytip 9 | Essential | 001077 |
| | Function Keytip | Essential | 001077 |
| | Numeric Keytip | Essential | 001077 |
| | Numeric Keytip | Essential | 001077 |
| | Numeric Keytip | Essential | 001077 |
| | Function Keytip | Essential | 001077 |
| | Keypad Sub-assembly | Essential | 004450 |
| | Silastic Rtv (glue) | Essential | 751801 |
| | Gloss White Label | Essential | 757451 |
| | Steel Keyboard S/A | Essential | 004450 |
| Level 2 | Body die casting | Essential | 4450 |
| | Numeric Keybodies | Essential | 4450 |
| | Function keybodies | Essential | 4450 |
| | E.S.D. shim | Essential | 1077 |
| | E.S.D. pressed shim | Essential | 1077 |
| | rubber mat with security | Essential | 1077 |
| | Membrane assy + security | Essential | 4450 |
| | Backplate | Essential | 4450 |
| | Pozidrive pan | Essential | 4401160 |
| | Membrane hydrophobic patch | Essential | 90 |
| | Resistor Assy | Essential | 1077 |
| | Taptite Pan | Essential | 401159 |
| | Heat sink compound | Essential | 79 |
| | Taptite pozipan | Essential | 401159 |
| | NCR security label | Essential | 90 |
| | Cable clip | Essential | 480700 |

## The parts for the MTO unit of analysis (MA Keypads)

| ***BOM Level*** | ***Item Description*** | ***Part Type*** | ***Generic Item No*** |
|---|---|---|---|
| ***Level 1*** | Carton | Essential | 751004 |
| | Carton insert | Essential | 751005 |
| | Tamper evident seal | Essential | 751801 |
| | Keypad Frame Moulding | Essential | 001034 |
| | Faceplate | Essential | 001034 |
| | Keytip Moulding | Essential | 001034 |
| | Key Locator | Essential | 001034 |
| | Front Seal | Essential | 001034 |
| | Pozipan Plastite Screw | Essential | 000077 |
| | Washer St | Essential | 403111 |
| | Washer Brass | Essential | 403211 |
| | Washer St Grover | Essential | 403121 |
| | Fullnut Brass | Essential | 404211 |
| | Backplate | Essential | 001034 |
| | Polydome membrane | Essential | 001034 |
| | E-Clip Bronze | Essential | 000090 |
| | Earth Strip | Essential | 001034 |
| | Key Shim | Optional | 001034 |
| | Keypad Label | Optional | 001034 |
| | Gloss white label | Optional | 757541 |
| | Key Stop Washer | Optional | 001034 |
| ***Level 2*** | Key pressl '1'- | Essential | 001034 |
| | Key pressl '2' | Essential | 001034 |
| | Key pressl '3' | Essential | 001034 |
| | Key pressl '4' | Essential | 001034 |
| | Key pressl '5.' Braille | Optional | 001034 |
| | Key pressl '6' | Optional | 001034 |
| | Key pressl '7' | Optional | 001034 |
| | Key pressl '8' | Optional | 001034 |
| | Key pressl '9' | Optional | 001034 |
| | Key pressl -Function | Optional | 001034 |
| | Key pressl '0'- | Optional | 001034 |
| | Key pressl -Function | Optional | 001034 |
| | Key pressl -Function | Optional | 001034 |
| | Key pressl -Function | Optional | 001034 |
| | Key pressl -Function | Optional | 001034 |
| | Key pressl -Function | Optional | 001034 |

## The parts for the MTS unit of analysis (lift PB bodies)

| BOM Level | Item Description | Part Type | Generic Item no |
|---|---|---|---|
| Level 1 | Main Body Moulding | Essential | 004042 |
| | Fixed Terminal | Optional | 003042 |
| | Screw Terminal Clamp | Optional | 004042 |
| | Comp2 Nylon Spacer | Optional | 004042 |
| | Plunger | Optional | 004042 |
| | Flexing Crossarm | Optional | 004042 |
| | Plunger Return Spring | Optional | 004042 |
| | Crossarm Return Spring | Optional | 004042 |
| | Lid Moulding | Essential | 004042 |
| | Terminal R/Conn Reinforced | Optional | 002087 |
| | Scr St Ch Hd | Optional | 401103 |
| | Illumination Terminal | Optional | 004042 |
| | Plain White S/Adh label | Optional | 757541 |
| Level 2 | Main body mould Polycarbonate | Essential | 322055 |
| | Plunger Delrin Acetal | Optional | 322091 |
| | Lid Moulding Polycarbonate | Essential | 322057 |
| | Terminal Strip | Optional | 135042 |

# Appendix 26 – Dewhurst Degree of Commonality Calculations

The Degree of commonality index (as defined in the glossary Appendix 1) was calculated across each UoA for BOM levels 1 and 2 components. The following formula was used based on Collier's formula:

The average number of incidences of the distinct component parts at BOM level 'x' for a particular UoA

$$= \frac{\text{total no. of incidences of BOM level 'x' components across end items}}{\text{no of distinct components at BOM level 'x' across end items}}$$

The table below shows the degree of commonality index calculations for each UoA

| | ***MTO (MA Keypads)*** | ***FPp (EPP Keypads)*** | ***MTS (PB Bodies)*** |
|---|---|---|---|
| Total no. of incidences of BOM Level 1 components | 458 | 963 | 95 |
| ***No of distinct components at BOM level 1*** | ***79*** | ***180*** | ***21*** |
| Total no. of incidences of BOM Level 2 components | 295 | 1080 | 35 |
| ***No of distinct components at BOM level 2*** | ***88*** | ***19*** | ***5*** |
| ***Degree of commonality index*** | | | |
| BOM level 1 components | 6 (24%) (body assembly) | 5 (7%) (keytips) | 5 (45%) (body assembly) |
| BOM level 2 components | 3 (14%) (keytips) | 57 (79%) (body assembly) | 7 (70%) (moulded parts) |
| ***Over both levels 1 and 2*** | ***5 (15%)*** | ***10 (14%)*** | ***5 (50%)*** |
| Upper Bound - no. of end items | 31 | 72 | 10 |

# Appendix 27 – Dewhurst Capacity Utilisation Calculations

Calculation of the cell design capacity for the MA and EPP keypads depended on a knowledge of the available labour levels at these cells. In the case of MA keypads this was clear because the cell was dedicated to their manufacture however in the case of EPP keypads this was not the case. The cell manufacturing EPP keypads (made up of work centres 702, 711 and 712) was dedicated to the customer NCR rather than the EPP keypads therefore it also manufactured the old range of NCR keypads. Fortunately the labour available for the production of the EPP keypads was recorded by production for the study period and split between the keypad assembling and configuring processes as detailed in Appendix 22.

**EPP Keypad Assembly Cell**

| *Wk. no* | *Week comm.* | *Keypad Assembly Output (keypads)* | *Processing Time (man min.)* | *Cell Output (man hours)* | *Labour level* | *Design Capacity (man hours)* | *Cap. Utilis. (%)* |
|---|---|---|---|---|---|---|---|
| 40 | **30-Sep** | 1800 | 7 | 210 | 6 | 225 | ***93*** |
| 41 | **7-Oct** | 2500 | 7.5 | 313 | 9 | 338 | ***93*** |
| 42 | **14-Oct** | 1600 | 7.5 | 200 | 9 | 338 | ***59*** |
| 43 | **21-Oct** | 1900 | 7.5 | 238 | 9 | 338 | ***70*** |
| 44 | **28-Oct** | 2400 | 7.5 | 300 | 9 | 338 | ***89*** |
| 45 | **4-Nov** | 2600 | 7.5 | 325 | 9 | 338 | ***96*** |
| 46 | **11-Nov** | 1850 | 7.5 | 231 | 9 | 338 | ***69*** |
| 47 | **18-Nov** | 2350 | 7.5 | 294 | 9 | 338 | ***87*** |
| 48 | **25-Nov** | 1800 | 7.5 | 225 | 9 | 338 | ***67*** |
| **49** | **2-Dec** | 2300 | 7.5 | 288 | **9** | 338 | ***85*** |
| 50 | **9-Dec** | 2215 | 7.5 | 277 | 9 | 338 | ***82*** |
| 51 | **16-Dec** | 2300 | 7.5 | 288 | 9 | 338 | ***85*** |
| 52 | **23-Dec** | 1200 | 7.5 | 150 | 9 | 338 | ***44*** |
| 1 | **30-Dec** | 0 | 7.5 | 0 | 9 | 338 | ***0*** |
| 2 | **6-Jan** | 0 | 5.5 | 0 | 6 | 225 | ***0*** |
| 3 | **13-Jan** | 600 | 5.5 | 55 | 6 | 225 | ***24*** |
| 4 | **20-Jan** | 1350 | 4.5 | 101 | 3 | 113 | ***90*** |
| 5 | **27-Jan** | 750 | 4.5 | 56 | 3 | 113 | ***50*** |
| **Averages** | | **1770** | **6.8** | **212** | **7.7** | **288** | ***71*** |
| | | | | | **Standard Deviation** | | ***27*** |
| | | | | | **Coeff of Variation (%)** | | ***38*** |

***Notes:***

The average, standard deviation and coefficient of variation calculations exclude the Christmas vacation weeks 52 and 1.

## Capacity Utilisation Calculations for the EPP Keypad Configuring Cell

| *Wk. no* | *Week comm* | *Keypad Configuring Output (keypads)* | *Processing Time (man min.)* | *Cell Output (man hours)* | *Labour level* | *Design Capacity (man hours)* | *Cap. Utilis. (%)* |
|---|---|---|---|---|---|---|---|
| 40 | **30-Sep** | 1769 | 4.5 | 133 | 6 | 225 | ***59*** |
| 41 | **7-Oct** | 974 | 4.5 | 73 | 6 | 225 | ***32*** |
| 42 | **14-Oct** | 831 | 4.5 | 62 | 6 | 225 | ***28*** |
| 43 | **21-Oct** | 1320 | 4.5 | 99 | 6 | 225 | ***44*** |
| 44 | **28-Oct** | 2572 | 4.5 | 193 | 6 | 225 | ***86*** |
| 45 | **4-Nov** | 2452 | 4.5 | 184 | 6 | 225 | ***82*** |
| 46 | **11-Nov** | 1813 | 4.5 | 136 | 6 | 225 | ***60*** |
| 47 | **18-Nov** | 1728 | 4.5 | 130 | 5 | 188 | ***69*** |
| 48 | **25-Nov** | 3097 | 4.5 | 232 | 5 | 188 | ***124*** |
| **49** | **2-Dec** | 2566 | 4.5 | 192 | **5** | 188 | ***103*** |
| 50 | **9-Dec** | 838 | 4.5 | 63 | 5 | 188 | ***34*** |
| 51 | **16-Dec** | 673 | 4.5 | 50 | 5 | 188 | ***27*** |
| 52 | **23-Dec** | 330 | 4.5 | 25 | 5 | 188 | ***13*** |
| 1 | **30-Dec** | 25 | 4.5 | 2 | 5 | 188 | ***1*** |
| 2 | **6-Jan** | 1060 | 4.5 | 80 | 3 | 113 | ***71*** |
| 3 | **13-Jan** | 962 | 4.5 | 72 | 3 | 113 | ***64*** |
| 4 | **20-Jan** | 1590 | 4.5 | 119 | 3 | 113 | ***106*** |
| 5 | **27-Jan** | 276 | 4.5 | 21 | 3 | 113 | ***18*** |
| ***Averages*** | | ***1533*** | ***4.5*** | ***115*** | ***4.9*** | ***185*** | ***62*** |
| | | | | | ***Standard Deviation*** | | ***31*** |
| | | | | | ***Coeff variation (%)*** | | ***51*** |

***Notes:***

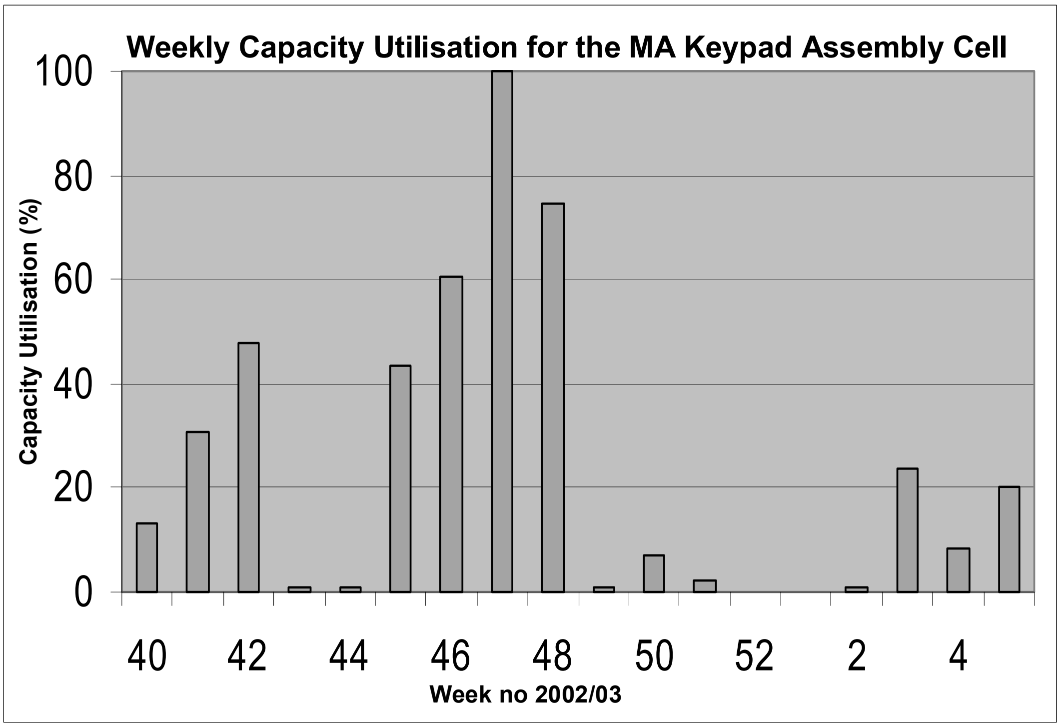
The average, standard deviation and coefficient of variation calculations exclude the Christmas vacation weeks 52 and 1.

## Capacity Utilisation Calculations for the MA keypads

| *Week no* | *Week comm* | *MA Keypad Output (keypads)* | *Cell Output (manhrs)* | *Labour level* | *Design Capacity (manhrs)* | *Capacity Utilisation (%)* |
|---|---|---|---|---|---|---|
| 40 | **30-Sep** | 30 | 10.0 | 2 | 75 | ***13*** |
| 41 | **7-Oct** | 77 | 23.0 | 2 | 75 | ***31*** |
| 42 | **14-Oct** | 146 | 36.0 | 2 | 75 | ***48*** |
| 43 | **21-Oct** | 1 | 0.6 | 2 | 75 | ***1*** |
| 44 | **28-Oct** | 1 | 0.7 | 2 | 75 | ***1*** |
| 45 | **4-Nov** | 119 | 32.7 | 2 | 75 | ***44*** |
| 46 | **11-Nov** | 159 | 45.3 | 2 | 75 | ***60*** |
| 47 | **18-Nov** | 285 | 75.0 | 2 | 75 | ***100*** |
| 48 | **25-Nov** | 216 | 55.9 | 2 | 75 | ***75*** |
| **49** | **2-Dec** | 1 | 0.7 | 2 | 75 | ***1*** |
| 50 | **9-Dec** | 18 | 5.2 | 2 | 75 | ***7*** |
| 51 | **16-Dec** | 5 | 1.8 | 2 | 75 | ***2*** |
| 52 | **23-Dec** | 0 | 0.0 | 2 | 75 | ***0*** |
| 1 | **30-Dec** | 0 | 0.0 | 2 | 75 | ***0*** |
| 2 | **6-Jan** | 1 | 0.8 | 2 | 75 | ***1*** |
| 3 | **13-Jan** | 61 | 17.8 | 2 | 75 | ***24*** |
| 4 | **20-Jan** | 23 | 6.4 | 2 | 75 | ***9*** |
| 5 | **27-Jan** | 51 | 15.0 | 2 | 75 | ***20*** |
| ***Averages*** | | ***75*** | ***20.4*** | ***2.0*** | ***75*** | ***27*** |
| | | | | ***Standard Deviation*** | | ***30*** |
| | | | | ***Coeff variation (%)*** | | ***111*** |

***Notes:***

- The average, standard deviation and coefficient of variation calculations excluded the Christmas vacation weeks 52 and 1.
- It was assumed that the two largest MA keypad orders each for 250 keypads and each started in week 47 were completed as soon as possible, the following week, hence the 100% capacity utilisation during week 47. However, this is an unlikely scenario since these orders were not due for delivery until 7th and 29th January 2003. Therefore the weekly capacity utilisation figures after week 47 are unlikely to be accurate. However, the average weekly capacity utilisation should still be reliable




**MA keypad Capacity Utilisation Discussion**

The average weekly capacity utilisation measured for the order-driven MA keypad assembly cell was much lower and more variable than for either of the EPP keypad cells. The capacity utilisation averaged at only 27% and the CV was as high as 111%. However although the average weekly capacity utilisation measure is reliable the individual weekly measures are not and therefore the CV is also unreliable. This is due to an assumption that the two largest MA keypad orders each for 250 keypads and each started in week 47 were completed as soon as possible, the following week. As illustrated in the chart above the result of this assumption is that capacity utilisation is 100% for week 47. However, this is an unlikely scenario since these orders were not due for delivery until 7th and 29th January 2003.