School of Mechanical, Materials and
Manufacturing Engineering

Managing Product Variety in International Supply Chains

by
Mahendrawathi Er

S.T., MSc.

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TABLE OF CONTENTS

Chapter 3 Research Methodology 78

Chapter 4 Empirical Study 99

ABSTRACT

In today's business environment, firms increasingly think in the context of a supply chain rather than a single factory and operate globally rather than in a single nation. At the same time, we have also witnessed increasing breadth in product ranges and accelerating rates of new product introduction in the marketplace. While there are potentially strong interrelationships between product variety and international supply chain management, the issues have been addressed separately in the research literature. Owing to this shortfall, this study investigates the issue of product variety in the context of international supply networks. More specifically, the study seeks to gain insights on different types of co-ordination and configuration of international supply network and to more deeply understand the impact of, and the interrelationships between, product variety, supply lead-time and demand uncertainty on the performance of an international supply chain. Empirical and simulation studies have been conducted to fulfil the above objectives.

The empirical study involves eleven manufacturing companies in Indonesia, belonging to both Multinational Corporations (MNC) and contract manufacturers, and one company in the UK operating internationally that owns manufacturing units as well as contracting out. The empirical study generated findings on configuration structures, co-ordination policies, and product variety impact and management. Based on their configuration and co-ordination strategies, MNC supply networks involved in the empirical study can be classified as supply networks that have *regional autonomous subsidiaries*, *regional clusters of subsidiaries* and *purely global supply*

network. Contract manufacturers' configurations may change from one selling period to another. More co-ordination efforts are found to be necessary in MNC supply networks compared to contract manufacturer supply networks. Although companies face different challenges with respect to product variety and uncertainties in demand and supply, the evidence shows that product variety principally affects the procurement of materials, as various products require different materials and parts. Product variety also affects production due to the need to conduct set-up activities.

To obtain a deeper understanding of the impacts of product variety, supply lead time and demand uncertainty on supply chain performance, a simulation study has been conducted. A simulation model was developed based on the insights obtained from the empirical study. The model represents a three-stage MNC supply network producing consumer goods in discrete manufacturing processes. Product variety is represented in the model by the use of different types of material required at different stages of the production process. An extensive set of simulation experiments concentrated on flow time and inventory performance.

Results from the simulation experiments show that increases in product variety extend the average flow time due to the need to conduct set-up activities. The impact of product variety on flow time depends on the severity of set-up and the stage at which variety occurs in the production processes. Variety occurring early in the production process and generating long set-up times has a more pernicious impact on average flow time compared to variety occurring later and requiring shorter set-ups.

Supply and demand uncertainty may affect the supply chain performance as it may delay the manufacturing processes. When supply lead-time is subject to uncertainty, materials may not be available at the right time for production. Similarly, demand uncertainty may lead to a situation where the available materials may not be adequate to meet the production requirements. The simulation results show that producing high variety when material delivery time is subject to uncertainty has a damaging impact on the two supply chain performance metrics – flow time and inventory level. The supply chain performance worsens with increasing level of supply uncertainty. Producing high variety when either aggregate-level or product-level demand is subject to uncertainty results in a higher level of inventory and longer average flow time. The worst performance in terms of average flow time and average inventory is evident when the supply chain produces maximum variety and both supply and demand are subject to uncertainty. The simulation study provides a guide to the magnitude of the impact in each case.

Findings from the empirical and simulation study are synthesised into a framework for understanding and managing product variety in international supply chains. The framework can be used to understand interrelationships between key factors in managing product variety in international supply networks and to identify potential strategies to mitigate the negative impact of those factors on performance

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LIST OF FIGURES

LIST OF TABLES

LIST OF PUBLICATIONS

1. Er, M. and MacCarthy, B.L., Investigating the Impact of Product Variety in International Supply Chains: A Simulation Study, *Proceedings of the 8th Cambridge International Manufacturing Symposium*, Cambridge, 25th – 26th September 2003, pp. 67 – 84.

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Chapter 1
Introduction

1.1 Background and motivation

The research reported in this thesis is driven by three prominent trends in today's business environment.

1.1.1 Globalisation of business environments

The first phenomenon is the globalisation of the business environment. Developments in information and communication technologies, the eliminations of trade barriers, the emergence of large 'domestic' market areas like NAFTA, overcapacities and significant cost disadvantages in highly industrialised countries are some factors contributing to the globalisation phenomenon (Arnold, 1999). As a result, more and more firms are involved to some degree in international business activities. Firms might simply import materials or export finished goods. More importantly, an increasing number of firms are collaborating in complex international supply networks.

1.1.2 Supply chain management

The increasing trend of firms expanding their perspective from a single company to a chain or network of organisations working together to deliver products and services to the end customer, a concept widely known as supply chain management, is the second phenomenon that underlies this study. Supply chain management has become a major interest for academics and industrialists in the past two decades (Harland, 1996; Tan, 2001; Chen and Paulraj, 2004).

1.1.3 Increasing product variety

In recent decades, we have witnessed an increasing breadth in product variety and increasing rates of new product introduction in the marketplace (Fisher et al., 1999; MacCarthy, 2001; Thonemann and Bradley, 2002). Whilst offering a wide variety of products may increase a company's market share and eventually contribute to higher profitability (Kekre and Srinivasan, 1990), it may result in more complex manufacturing operations (MacDuffie et al., 1996), as well as more complicated supply networks (Milgate, 2001).

1.2 Description of the research area

The literature on international business has traditionally focused more on the marketing, economic or financial aspects of doing business internationally and less on manufacturing or operations management aspects. More recently, as more and more manufactured goods cross national boundaries and a larger number of companies invest in foreign manufacturing activities (Ferdows, 1989), the study of international operations and international manufacturing has received increasing attention.

Porter (1986) introduced two important aspects to be considered in developing international operations: configuration and co-ordination. Configuration deals with the structure as well as the arrangement (location and function allocation) of the network of factories. Co-ordination deals with the way the international network of facilities is integrated or linked in order to function as desired. Following Porter's work, many authors have asserted the importance of strategic orientation, product and industry characteristics in determining international configuration decisions (Ferdows, 1989; DuBois, 1993). There is also a great deal of work on classification of companies operating internationally based on configuration and co-ordination characteristics (Ferdows, 1989; Roth, 1992; Harzing, 2000). This stream of literature focuses more on issues such as location and configuration decisions with less attention being paid to the co-ordination of day-to-day operations of international supply networks. Furthermore, many of the works focus on the Multinational Corporation's (MNC) supply network, whilst other types of ownership such as subcontracting, or types of relationship that lie between owning foreign facilities and subcontracting, have received less attention. Works that explore the performance of international supply networks applying specific configuration and co-ordination strategies are also lacking in the current literature.

Literature in supply chain management does emphasise the importance of understanding the structure of the network (Stewart, 1997; Lambert et al., 1998; Fine et al., 2002) and the co-ordination of elements in the supply chain (Slack et al., 2004). A number of seminal works in supply chain management aim to develop supply chain strategies that match the level of demand uncertainty (Fisher, 1997) as well as supply uncertainty (Lee, 2002) inherent in the supply chain.

Traditionally, the international dimension is not explicitly included in the definition or context of supply chain management literature. As an increasing number of products in the market today are produced by an elaborate international web of suppliers and assemblers, the international factor can be considered as a common characteristic of a supply chain (Akkermans, 1999; Wisner et al., 2004). Several authors have addressed the challenges in managing international as opposed to 'domestic' supply chains. Houlihan (1987) highlights the fact that developing international supply chains potentially increases a firm's business complexity and exposes them to greater risks and vulnerability. Prater et al. (2001) asserted that firms' international supply chains frequently limit performance in many attributes associated with agility. However, very little work explicitly relates the configuration and co-ordination strategies with other factors in managing supply chains including supply and demand uncertainty. Levy (1995) is among the few works that developed a simulation model to investigate the impact of different choices of configurations, supply and demand uncertainty on the performance of an international supply chain.

Whilst the works in the international supply chain literature highlight some of the challenges associated with international supply chain management, the issue of managing product variety in international supply chains has not been adequately addressed. Research on product variety focuses mainly on investigating the impact of product variety on a single manufacturing company operation (Anderson, 1995; Fisher et al., 1995; MacDuffie et al., 1996; Fisher and Ittner, 1999). Different businesses face different variety-related problems, hence much of the work on product variety focuses on addressing the issue of product variety in a specific industry. More recently, a number of authors have addressed the issue of product variety in the wider context of supply chain as opposed to a single manufacturing facility (Randall and Ulrich, 2001; Thonemann and Bradley, 2002). However, the potential impact of product variety on international supply chain performance has not been addressed.

In reality, many firms are faced with increasing product variety while managing their international network of suppliers, manufacturers and customers. Lee (2002) states that, "managing supply chains effectively is a complex and challenging task, due to the current business trends of expanding product variety, short product life cycle, increasing outsourcing, globalisation of business and continuous advances in information technology". In today's business environment, the management of product variety and international supply networks are inter-related areas that need to be approached simultaneously.

Product variety may occur as a result of differences in materials and or production processes happening in various stages of the value chain. Several authors have mentioned the potential effect of product variety on supply systems (MacDuffie et al., 1996; Milgate, 2001). When product variety requires different types of materials, a more complex supply network configuration will have to be managed since more suppliers are usually involved to supply the materials. This indicates that more product variety potentially adds complexity to the configuration and co-ordination of supply networks (Milgate, 2001).

High product variety also creates uncertainty in demand (Randall and Ulrich, 2001). Fisher (1994) argues that having a wider range of product variants means that it will be more difficult to predict the demand at the product level. In the presence of demand uncertainty, it is difficult to precisely match supply with demand (Randall and Ulrich, 2001). The possibility of a mismatch between supply and demand causes disruptions to production, particularly when demand exceeds supply. It also generates costs associated with inventory holding cost, product markdown costs when supply exceeds demand, and the costs of lost sales when demand exceeds supply (Randall and Ulrich, 2001).

The challenge of managing product variety is amplified further when the supply chain operates internationally. Separating value chain activities across different elements located in different regions in the world demands more co-ordination efforts to ensure smooth flow of information, materials and products across elements of the supply network. Geographical distance between elements in international supply networks is also associated with long lead-time and greater delivery uncertainty (Levy, 1995). As a consequence, some of the value chain activities, particularly procurement of materials, have to be conducted prior to the arrival of actual demand. This exposes the supply network to greater risks of a mismatch between supply of materials procured based on forecasts and actual demand. It might also limit the supply network's ability to respond to any changes in the marketplace.

All the above arguments indicate that managing product variety in international supply networks is a timely issue that needs to be investigated further. There is a need to relate the issue of product variety with other factors in managing international supply network including configuration, co-ordination, as well as the levels of supply and demand uncertainty. This will enable exploration and investigation of the potential impact of different factors on the performance of international supply networks. Better understanding of this area will provide a basis to identify solutions to address the problems of managing product variety in international supply networks.

1.3 Goals and objectives

The main goal of this study is to investigate the problems of managing product variety in international supply networks. More specifically, the research objectives are to:

1. Investigate the configuration, co-ordination and product variety issues of real international supply chains with different ownership patterns.
2. Investigate through an empirical study how product variety relates to, and interacts with other challenges in managing international supply networks, particularly demand uncertainty and supply uncertainty.
3. Investigate through simulation study the impact of product variety, supply uncertainty and demand uncertainty on the performance of international supply networks with certain configuration and co-ordination strategies.
4. Propose a framework that enables the evaluation of problems in managing product variety in international supply networks and the identification of potential strategies to address the problems.

These objectives are tackled through a detailed and structured analysis of relevant literature, through an extensive field study of a wide range of cases and through a simulation study.

1.4 Scope of the study

The issue of managing product variety in international supply networks has received virtually no attention in the existing literature. The problem is particularly complex with many inter-related factors. Thus, to avoid dealing with exceedingly complex situations whilst the study is still in the initial stage, the problems will be addressed with the following scope:

1. Immediate supply network perspective. A wide definition of supply chain or network comprises the entire value adding activities from supplier's supplier to customer's customer (total supply network perspective proposed by, to name but one, Slack et al., 2004, pp. 163 – 165). However, a practical approach to supply chain management is to consider only strategically important suppliers (Tan, 2001) or key linkages in the value chain. In this study, the configuration and co-ordination of international supply networks is captured from the perspective of the case companies involved in the empirical study. In other words, the supply network is drawn from each case company's perspective. The co-ordination aspects are observed from the information and materials flow among each case company and its immediate (direct) suppliers and customers.

2. Focusing on the operations management perspective. Many aspects of this study might be addressed from various perspectives. For example, the decisions involved in developing international supply chains and on ownership may be influenced by economics, marketing and political factors. Similarly, decisions regarding a company's breadth of product

ranges have been investigated in the economics and marketing literature. Whilst insights from various areas of study are acknowledged, the study here focuses on addressing the issue of product variety in international supply chains from an operations management perspective.

Other considerations and assumptions that do not apply to the entire study will be noted in the relevant parts of the thesis.

1.5 Outline of the thesis

This thesis is structured into 10 chapters as follows:

Chapter 1 Introduction

Chapter 1 describes the background, goals and objective of the study. It also provides the outline of the thesis.

Chapter 2 Literature review

In chapter 2, various streams of literature including international operations, general and international supply chain management and product variety are reviewed. Gaps in the current literature, which provide direction for the study, are identified in this chapter.

Chapter 3 Methodology

Chapter 3 describes the methodology used in conducting the research. Firstly, research questions to be addressed are identified. This is followed by a description of the stages of the empirical study. Justification for the use of simulation to study product variety in international supply networks and the nature of the simulation study conducted are provided.

Chapter 4 Empirical study

Chapter 4 describes the empirical study. First, a brief overview of each case company is provided. This is followed by analysis of the configuration and co-ordination strategies of each case company. The second part of chapter 4 discusses the challenges facing the international supply networks. The challenges facing each case with respect to product variety are discussed. This is followed by an assessment of the level of demand and supply uncertainty faced by each case company.

Chapter 5 Model development

Chapter 5 describes the model development based on relevant insights from the empirical study. Insights regarding configuration aspects are used to develop the structure of the model, whilst information on co-ordination aspects are used to develop the logic and operating policies of the model. The overview of the simulation environment, simulation experiments, factors and levels are provided. This is followed by a description of the mechanism of each module in the simulation model. The setting of reference input data and parameters controlling supplier delivery time, volume and mix uncertainty is described. Finally, verification and validation of the simulation model is provided.

Chapter 6 Investigating the impact of product variety and supply lead-time uncertainty

Chapter 6 discusses the results from the first set of simulation experiments investigating the impact of product variety and supply lead-time uncertainty on the performance of the international supply network whilst demand is predictable. The experimental factors and their levels, input parameters and the design of the experiments are described. This is followed by analysis of results. The general and practical implications of the findings are discussed.

Chapter 7 Investigating the impact of product variety and demand uncertainty

Chapter 7 describes the findings from simulation experiments investigating the impact of product variety and different classes of demand uncertainty whilst supplier lead-time remains constant. The same structure as in chapter 6 is followed. Firstly, experimental factors and levels, input parameters and design of the simulation experiments are described. This is followed by analysis of results and discussion on general and practical implications of the findings.

Chapter 8 Investigating the impact of product variety, supply and demand uncertainty

In chapter 8, results from the final set of experiments investigating the impact of product variety, supply lead-time and demand uncertainty are provided. The chapter begins by describing the experimental factors and level, the input parameters and design of simulation experiments. Analysis of the results is then carried out. The general and practical implications from the results are discussed.

Chapter 9 Framework for managing product variety in international supply chains

Chapter 9 synthesises the findings from the literature, the empirical study and the simulation study. It describes a general framework to: 1) understand the inter-relationships between product variety, configuration, co-ordination, supply and demand uncertainty, 2) understand, and address the negative impact of these factors on international supply chain performance.

Chapter 10 Conclusion and further studies

The final chapter summarises the research contributions, important findings from the study and proposes a number of potential areas for further study.

Chapter 2
Literature Review

2.1 Introduction

Addressing the issue of product variety as part of international supply network management requires understanding of a wide range of issues. The management of companies operating internationally begins with understanding the way the network of factories are configured and co-ordinated. The organisation of a supply network encompassing degree of vertical integration and the nature of relationships among elements are important aspects in managing international supply networks. Effective management of supply networks also means understanding the source of uncertainties both from the supply and demand sides that affect the day-to-day operation of the supply networks and devising strategies to cope with the uncertainties. The major concern for companies offering wide product variety is to minimise the negative impacts of variety on their operations. This requires understanding of the factors causing increases in product variety, the mechanisms by which variety affect the operations and the strategies to mitigate the negative impacts of product variety on the operations. This chapter reviews literature that provides relevant insights on these issues.

The chapter is organised as follows. Relevant works in the international operations literature addressing configuration and co-ordination, classification of the international network of factories, development of international manufacturing strategy and ownership in international operations are covered in section 2.2. This is followed by a review on supply chain management literature addressing the structure of supply chains, vertical integration decisions, supply relationships, the issues in supply chain management including the Bullwhip Effect, and supply and demand uncertainty (section 2.3). Literature that specifically highlights the challenges associated with managing international supply chains as opposed to 'domestic' supply chains, including difficulty in integrating and co-ordinating activities, long lead-times and greater delivery uncertainty are described in section 2.3.6. Section 2.4 is dedicated to review the literature on product variety. Findings from the various bodies of literature are synthesised in section 2.5. Gaps found in the existing literature, which provide directions for this study, are identified in the final section.

2.2 Literature on international operations

2.2.1 Development of international operations

International business is not a new research subject. Since the mid-1950s, when the growth in world trade began to significantly exceed the growth in world GNP, international business has emerged as an important area of study (Porter, 1986). Although there has been a large body of literature on international business, the points of interest are continually evolving. Porter (1986) states that previous studies in international business mainly addressed the issue of comparative advantages among countries, the ability of multinational companies to exploit intangible assets and other general problems of doing business in a foreign country. He argued that the literature shed little light on how to select and develop a firm's international strategy.

As pointed out by Ferdows (1989), the literature puts the attention mainly on the marketing, financial or economic aspects of internationalisation and less on the operations or production management. More recently, the strategic role of manufacturing has been increasingly recognised. At the same time, due to more intense internationalisation in manufacturing companies – the fact shows that more and more manufacturing goods are crossing national boundaries and a larger number of companies are investing in foreign manufacturing activities - international operations or international manufacturing study has gained more attention (Ferdows, 1989; Prasad et al., 2001).

According to Bolisani and Scarco (1996) the issues of internationalisation are evolving around three fundamental questions:

- Why pursue international operations?
- Where to operate?
- How to manage the international operations?

Bolisani and Scarco (1996) identified four main goals that companies seek from internationalisation. These can be summarised as follow:

- *Natural Resource Seekers* are companies that invest abroad to get specific low cost resources such as materials, labour, etc.
- *Market Seekers* are referring to companies that invest in a particular region to supply products in the same or an adjacent area. This is usually the case for companies aiming at penetrating new or rich markets.
- *Efficiency Seekers* are companies that consider foreign investment as a way of rationalising the existing structure, thus gaining from its

geographically dispersed activities. This might include advantages via economies of scale, scope or risk diversification. For example, an apparel manufacturer may choose to produce high-quality product lines locally whilst casual and low-cost lines are manufactured abroad.

- *Strategic Asset Seekers* are companies that try to gain long term strategic advantages by acquiring the assets of foreign corporations. For example the acquisition of trade marks, searching for specific managerial or technological competencies.

Several authors including Harzing (2000) and Ferdows (1989) use the main goals or strategic orientations of developing international operations as bases for classifying companies operating internationally.

The decision on where to locate operations has been a subject of interest in both international operations and general operations management literature. Several factors are identified as important criteria in international location decisions including: availability of nation-specific resources such as labour skills (Bolisani and Scarco, 1996), costs associated with logistic, labour, land and energy (Slack et al., 2004, pp. 174 – 178), access and proximity to customers, tariff barriers, government taxes and incentives (Wisner et al., 2004, pp. 342 – 344). For a more comprehensive list of factors affecting international manufacturing location decisions see MacCarthy and Atthirawong (2003).

According to Bolisani and Scarco (1996) the management of international operations mainly relates to:

- Configuration of production resources, which concerns the number of plants and their sizes as well as operational flows among these plants.
- Co-ordination mechanisms that involve several things including degree of autonomy allowed to foreign plants, global and local planning criteria, personnel management, industrial engineering, product design and quality control policies.
- Technological investment that mainly concerns the type of technological investments required in supporting the operation.

2.2.2 Configuration and co-ordination in international operations

Porter (1986) is one of the earliest authors who proposes the concept of configuration and co-ordination in international operations. His work is aimed at helping firms in selecting and developing their international strategy. Porter (1986) introduces the concept of **Value Chain** in investigating the source of competitive advantage. He suggests that "every firm is a collection of a discrete activities performed to do business that occur within the scope of the firm". These activities, which he called *value activities,* are connected through linkages. He argued that, "There are many linkages that connect activities, not only within the firm but also with the activities of its suppliers, channels, and ultimately its buyers. The firm's value chain resides in a larger stream of activities that I term the **Value System...**"

Companies that operate internationally must decide how to spread the value chain activities across different countries and at the same time determine how those activities should be linked to one another. According to Porter, the distinctive issues in international - as opposed to domestic - strategy can be structured around two dimensions: *configuration and co-ordination* of companies operating internationally. Configuration of a firm's worldwide activities is concerned with the structure of the network i.e. where and in how many places in the world each activity in the value chain is conducted. Configuration ranges from *concentrated* - that is performing all the value chain activities in one location to serve the world - to *dispersed*, which means performing various activities in the value chain in different locations. Co-ordination on the other hand is defined as the manner in which the activities performed in different countries are linked and integrated. It ranges from *none*, which implies full autonomy for each plant, to *highly co-ordinated* where the plants are tightly linked to one another and centrally controlled.

2.2.3 Classification of companies operating internationally

Since introduced by Porter (1986) there has been a large body of literature dedicated to study the configuration and co-ordination dimensions. Some of the important literature sources are summarised in table 2.1. One of the most common issues addressed in international operations literature is classification of internationally operating companies based on similarities and differences in the configuration and co-ordination dimensions. Ferdows (1989) proposed a classification for subsidiaries of multinational companies based on the primary strategic reasons for establishing the plants and the level of technical activities assigned to the plant. Ferdows identified six strategic roles of a plant in international networks: *offshore, outpost, server, source, lead and contributor.*

Table 2.1 Summary of international operations literature

Author	Method	Key Issues	Results
Ferdows (1989)	Case Studies with eight MNC in electronic industry	Classification based on primary reason for establishing the plant & task allocation (*configuration*)	Map of MNC subsidiary: - Offshore - Outpost - Server - Source - Lead - Contributor
Roth (1992)	Survey on 126 US Medium-sized companies	Classification of sample based on dispersion of activities (*configuration*) & co-ordination	Archetypes of US medium-sized companies: - Concentrated hub - Local innovator - Transnational innovator - Regional federation - Primary global
Harzing (2000)	Typology development tested in 166 subsidiaries of MNC	Classification based on strategy followed by headquarter, organisational design (*configuration*) & subsidiary role, local responsiveness and interdependence (*co-ordination*)	Typology of MNC: - Multidomestic - Transnational - Global
DuBois et al.(1993)	Conceptual framework & case studies with 16 companies	Investigating major factors that may influence international manufacturing configuration (IMC) decisions	Important factors that influence IMC: - Firm's competitive priorities - Market orientation - International experience - Product characteristics
McGrath & Bequillard (1989)	Conceptual framework	Developing *international manufacturing infrastructure* – mechanism to co-ordinate and manage international manufacturing activities (*Co-ordination*)	International manufacturing infrastructure: - Localisation of manufacturing strategy - International supply/demand management - Global and local purchasing - Product/process technologies - General organisation & integration mechanism
Martinez & Jarillo (1991)	Survey on 50 multinational company subsidiaries	Investigating the connection between MNC strategy and their use of co-ordination mechanism	Co-ordination mechanism is classified into formal and informal, and it was found that subsidiaries pursuing high integration strategies with their parents make use of both formal and informal co-ordination more extensively
Meijboom &Vos (1997)	Literature review and case studies with 4 internationally owned company in Thailand	Combine Ferdows (1989) work on configuration and McGrath and Bequillard (1989) work on co-ordination	Configuration decisions lead to a certain form of co-ordination and thus co-ordination issues have to be explicitly considered in configuration decisions

Roth (1992) determines the basic configuration and co-ordination 'archetypes' for 126 US medium-sized companies by identifying whether a certain part of the value chain – such as manufacturing, sales, marketing, product and process innovation, etc - was performed in a single country or in multiple countries. For activities performed in multiple countries, respondents also had to indicate whether the activities were co-ordinated globally, regionally, or managed locally. While the two previous authors based their classification heavily on allocation of task and co-ordination issues, Harzing (2000) incorporates more general issues such as strategy of headquarters, organisational design and subsidiary role, local responsiveness and interdependence in developing typology of multinational subsidiaries.

Finally, despite different ways proposed by these authors in classifying internationally operating companies, one profound idea that is commonly used – explicitly or implicitly - in the classification is the strategic orientation or goals that a company pursues in international operations: market responsiveness, efficiency/cost or a combination of both.

2.2.4 International manufacturing strategy

In addition to the work on classification of companies operating internationally, there are also streams of international operations literature that are drawn from manufacturing strategy literature. DuBois et al. (1993) combine the manufacturing strategy with international operations literature and developed a framework to identify the major factors that may influence firms' international manufacturing configuration decisions. They highlighted that firm's competitive priorities (expressed in terms of different emphasis put on four competitive measures including efficiency/cost, quality, flexibility and delivery dependability), product characteristics, market orientation, and international experience are key factors in the development of international manufacturing configurations.

McGrath & Bequillard's (1989) work in international manufacturing strategy focused more on the co-ordination dimensions. They defined international manufacturing strategy as the overall plan of how the company will manufacture products on a worldwide basis to satisfy demand worldwide. Several basic international manufacturing strategies are listed which include: home country manufacturing, regional manufacturing, co-ordinated global manufacturing, and combination of regional and co-ordinated global manufacturing. Based on these strategies, McGrath and Bequillard (1989) derive organisational and infrastructural mechanisms - which they refer to as *international manufacturing infrastructure* - required to co-ordinate and manage international manufacturing activities. The international manufacturing infrastructure covers several important points as follows:

1. Localisation of manufacturing strategy
2. International supply/demand management
3. Global and local purchasing techniques
4. Product/process technologies and new product introduction strategies
5. General organisation and integration mechanism

Martinez and Jarillo (1991) on the other hand, conduct a survey on fifty subsidiaries of Multinational Corporations (MNC) in order to explore the relationship between the strategy of an MNC and the mechanisms of co-ordination employed to implement that strategy. Co-ordination mechanisms can be divided into formal and less formal. Formal co-ordination includes centralisation, formalisation, planning, output control and behavioural control, while informal mechanisms consist of three managerial tools: lateral relations, informal communication and organisational culture. From their survey, Martinez and Jarillo (1991) find that subsidiaries pursuing a higher level of integration with their parents make use of both formal and informal co-ordination mechanisms more extensively.

Meijboom & Vos (1997) attempt to explicitly correlate configuration and co-ordination dimensions. They combine Ferdows' (1989) idea of a firm's strategic role (configuration) and McGrath & Bequillard's (1989) work on international manufacturing infrastructure (co-ordination) in assessing four case studies of internationally owned (Dutch) production plants in Thailand. They argue that configuration decisions include the allocation of tasks and resources to a plant at a certain location and the level of sophistication of the plant. These decisions influence the form of co-ordination required to manage the plant. Thus, Meijboom & Vos (1997) propose that co-ordination issues need to be considered explicitly in making configuration decisions.

2.2.5 Ownership in international operations

While the international operations literature reviewed in the previous sections mainly address the issues facing multinational companies and their network of foreign subsidiaries, other types of ownership arrangement exist in international business. According to Bennett (2001), ownership arrangements may take the form of straightforward selling (i.e. no ownership involved), franchising, contracting, licensing, co-production, joint ventures or a wholly owned subsidiary (complete ownership of the foreign operation). Bennett (2001) argues that the type of ownership arrangement is a critical factor in determining the importance of operational and co-ordination issues in international operations. As shown in figure 2.1, Bennett argues that increasing the extent of ownership means that the operational issues, such as decisions on types of product design, local sourcing, material management etc, become more important. On the other hand, as the extent of ownership decreases, these decisions become less important as some of the decisions are deployed to other elements in the network. However, this means co-ordination issues become increasingly important as other elements will be part of a network rather that a sub-unit within an integrated network.

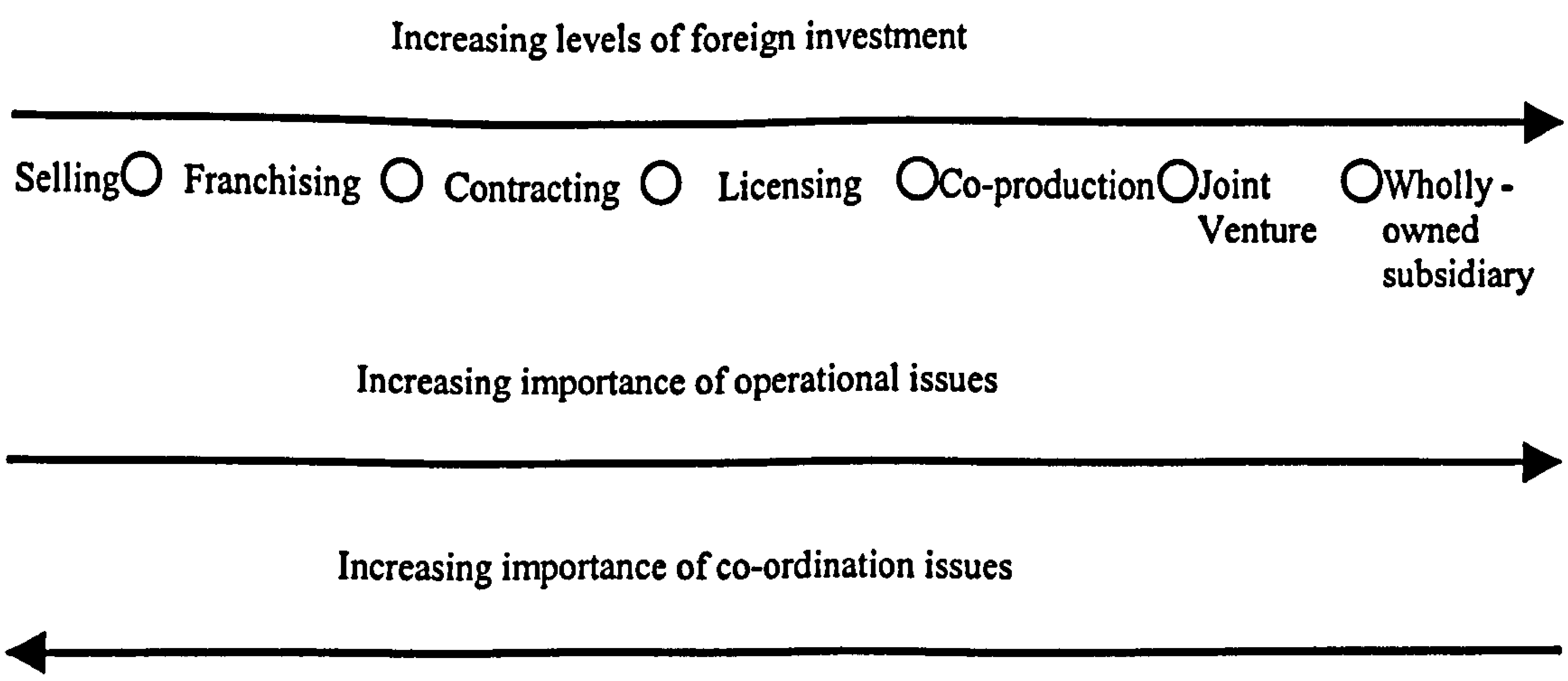


Figure 2.1 Ownership arrangements and the importance of operational and co-ordination issues (Source Bennett, 2001)

2.3 Literature on supply chain management

In the last two decades, there has been increasing interest in supply chain management concepts. Research in this area is well documented in the literature. Some of the important works relevant to this study are reviewed in this section. A summary of this literature is illustrated in figure 2.2.

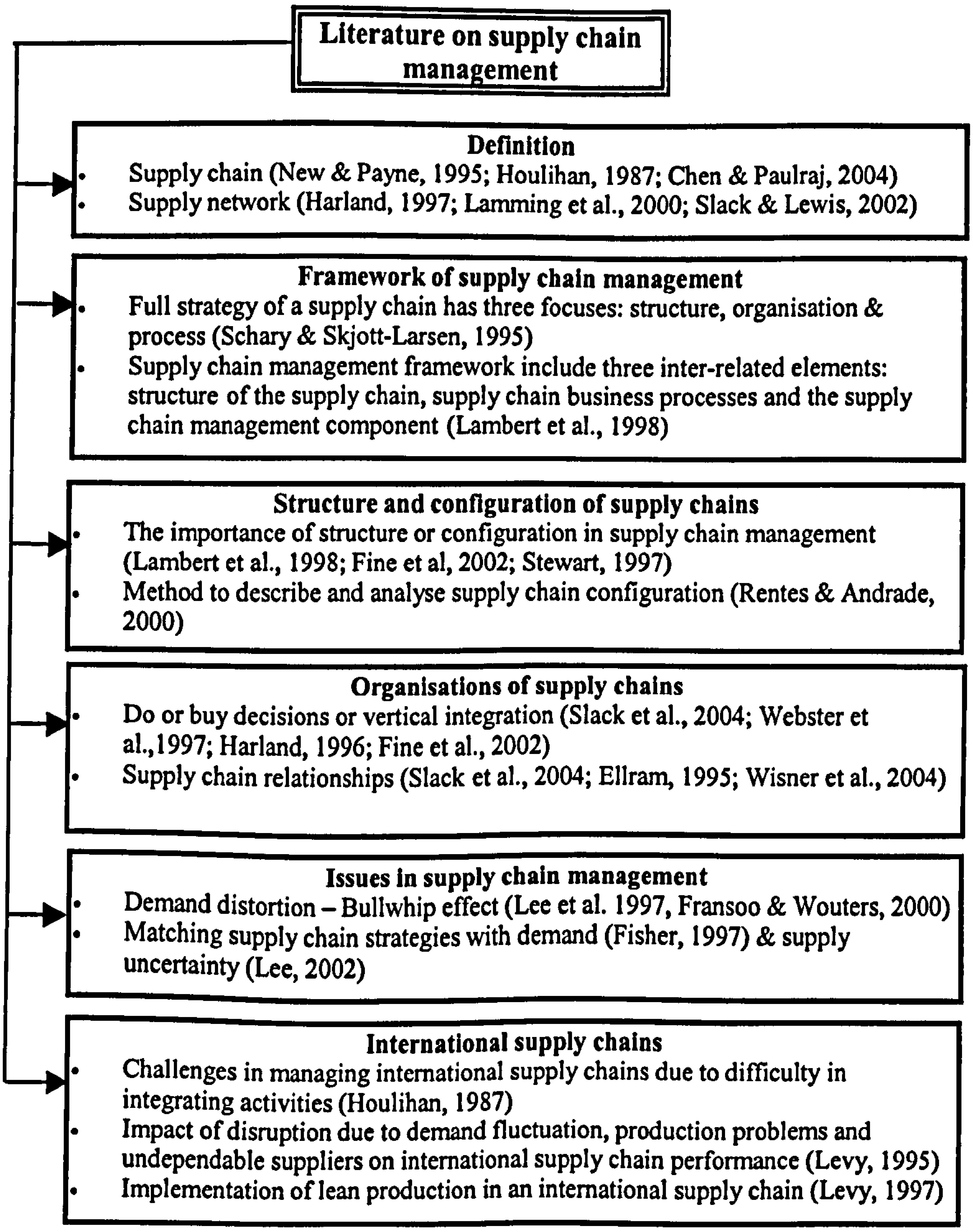


Figure 2.2. Summary of literature on supply chain management

First, definitions of the terms used in supply chain management literature are reviewed. This is followed by a review on works that provide general framework of supply chain management. Streams of literature that provide insights on the structure or configuration of supply chain and the issues of supply chain organisations, particularly with respect to vertical integration and supply relationships, are reviewed. A great deal of works in supply chain management have been dedicated to address the issues of information distortion, also known as bullwhip effect, as well as supply and demand uncertainty in managing supply chains. Finally, several literature highlighting the challenges associated with international supply chain management are discussed. Detailed descriptions of these streams of literature are provided in the following sections.

2.3.1 Definition and terminologies

The focus in many industrial and business sectors today has expanded from management of a single company to a chain or network of organisations working together to satisfy the end customer's expectations i.e. supply chain management (SCM). The term supply chain management is introduced in the early 1980s, as Oliver and Webber (1992) discuss, to capture the potential benefits of integrating purchasing, manufacturing, sales and distribution. Since then, the term supply chain management (SCM) has been widely used in the literature, often interchangeably with other terms such as **value chain** or **value stream.**

New and Payne (1995) description of value chain activities in a firm begins with the extraction of raw materials or minerals from the earth, through to manufacturers, wholesalers, retailers, and the final users and where appropriate recycling or re-use of products or materials. Tan (2001) argues that the value chain is too complex to achieve a full integration of all business entities, and hence, a practical approach to supply chain management is to consider only strategically important suppliers in the value chain. A narrower and more practical definition of supply chain management is provided by Houlihan (1987). He defined supply chain management as "the integration of the various functional areas within an organization to enhance the flow of goods from immediate strategic suppliers through manufacturing and distribution chain to end user".

Based on a comprehensive review on SCM literature, Chen and Paulraj (2004) suggest that many authors have used the term SCM to explain: 1) the planning and control of materials and information flows not only internally within a company but also between companies; 2) strategic inter-organisational issues, 3) alternative organisational form, 4) the relationships between a company and its supplier.

In the development of SCM, many authors extend the term supply chain to **supply network.** The incorporation of the term "network" into supply chain management research is an attempt to make the concept wider and more strategic by harnessing the resource potential of the network in a more effective manner (Lamming et al., 2000). According to Slack and Lewis (2002, p. 181), "a supply network is an interconnection of organisations which relate to each other through upstream and downstream linkages between the different processes and activities that produce value in the form of products and services to the ultimate consumer".

Harland (1996) defines supply networks simply as sets of supply chains, describing the flow of goods and services from original sources to end-customers. Whilst supply chains are sometimes represented in a simplistic, linear and unidirectional model, the supply network concept describes lateral links, reverse loops, two-way exchanges etc., encompassing the upstream and downstream activities, with a focal firm as the point of reference (Lamming et al., 2000). Despite the differences pointed out by these authors, the term supply chain and supply network are often used interchangeably.

Slack et al. (2002, p. 182) defines a company drawing the network and thus is at the centre of the network as the **focal company**. A focal company's supplier and its supplier's supplier are referred as the upstream side, while its customer and customer's customer form downstream side of the network. Various operations within the focal company are referred as the **internal supply network**. The focal company has direct contact with suppliers and customers forming the **immediate supply network**. Finally, the linkages of suppliers to the focal company's supplier, and customers to focal company's customers form its **total supply network**.

2.3.2 Framework of supply chain management

Schary and Skjott-Larsen (1995) state that the full strategy of the supply chain has three points of focus: **structure, organisation and process**, which operate at two levels i.e. corporate and operations. At a strategic level, supply strategy concerns the supply **structure** – location of facilities and processes by stages within the supply chain – and organisations. In defining stages of the value-adding process in product flow, Schary and Skjott-Larsen (1995) refer to the value chain/system concept proposed by Porter (1986). They argued that the value system encourages the entire system to think in terms of activities and stages of processing rather than in terms of organisations. However, a series of organisational relations is at the heart of the value system. At the same time, separating stages not only establishes the structure of production and supply but also enables identification of core activities that are essential for the organisation to maintain its competitive advantage.

The second focus of supply strategy covers the issues of **organisations** and their boundaries that will define the terms of co-ordination and inter-organisational relationships. This aspect determines which organisation takes direct responsibility for each stage of the supply process. The third focus proposed by Schary and Skjott-Larsen (1995) is on **process**, which covers the issues of planning, performing and controlling operations. Processes need to be co-ordinated in order to ensure their continuity and their ability to respond as an integral unit in order to achieve the overall objectives of the system.

Similar to Schary and Skjott-Larsen's (1995) ideas, Lambert et al. (1998) proposed a supply chain management framework that encompasses the combination of three closely inter-related elements: the **structure** of the supply chain, the supply chain business **processes** and the supply chain **management** components. The supply chain structure is the group of members, the structural dimensions of the group (horizontal and vertical structure and the focal firm's position in the horizontal structure) and the links between members of the supply chain. Business processes are the activities that produce a specific output of value to the customer. Finally, the management components are the managerial variables by which the business processes are *integrated* and *managed* across the supply chain.

2.3.3 Structure and configuration of supply chains

The frameworks provided by Schary and Skjott-Larsen (1995) and Lambert et al. (1998) both highlight structure as an important element in supply chain management. Fine et al. (2002) add that understanding and redesigning a certain value chain begins with a map, one that identifies the organisations involved, the capabilities they bring to the value proposition, and the technological contribution each makes to the company's products and services. Stewart (1997) lists definition of the current and ideal supply chain configuration as the second level of assessment in the Supply Chain Operations Reference Model (SCOR) - a cross industry framework of evaluating and improving enterprise-wide supply chain performance and management.

As the role of configuration or structure is increasingly realised Rentes and Andrade (2000) propose a method to describe or analyse the configuration of international supply chains. They extend the Value Stream Mapping tools – originated from lean production movement (see Hines et al., 1998) to visualise and analyse the supply chain configuration, material and information flow. They propose three levels of modelling: starting with a general overview of the supply network at the first level and cascading to more detail descriptions of information, material flow and internal processes in the second and third level.

According to Fine et al. (2002), the design of a company's value chain has traditionally been viewed as a static enterprise, the assembling of a fixed set of suppliers and distribution channels to attain and maintain competitive advantage. However, with the fast changing pace of today's technologies and business environment, they argue that ongoing value chain assessment and design at the corporate level have become a necessity. They highlight further that in this ever changing environment, "A company's real core capability and the only sustainable one is its ability to design and redesign its value chain in order to continually find sources of maximum, albeit temporary, advantage".

2.3.4 Organisations of supply chains

According to Schary & Skjott-Larsen (1995), organisations of supply chains include: 1) determining which organisation is responsible for each stage of supply process and 2) inter-organisational relationships. The first point concerns how much of the supply chain or network a company should own, which is often called a do or buy decisions.

2.3.4.1 Vertical integration (do or buy decisions)

The general notion underlying this issue is that due to the complexity of product, no single company has all the necessary knowledge about either the product or the processes to completely conduct design and manufacturing of the product in- house (Fine and Whitney, 1996).

The do or buy decision will determine the degree of vertical integration or disintegration of a supply chain or network. According to Webster et al. (1997), within a vertically integrated supply chain, a single enterprise retains ownership and or control over the others, through merger or other form of formal corporate alliance with enterprise elsewhere in the chains. On the other hand, within a vertically disintegrated supply chain, production can be subcontracted or outsourced down through various levels from the original principal to several independent enterprises.

The decision of conducting the activities in house or buying from an outside organisation is a strategic decision that can impact an organisation's competitive position (Wisner et al., 2004, p. 43). Owning certain parts of the network is preferable to some businesses as it ensures dependable delivery of input goods and services, enables control over product or service quality and helps in understanding other activities in the supply network (Slack and Lewis, 2002, pp. 189 – 191). However, the potential pitfalls of vertical integration are also commonly known, including: the loss of volume flexibility and distracting companies from core activities. Furthermore, integrated businesses face the danger of becoming locked into inappropriate technologies (Harland, 1996).

Many authors suggest that the trend in the business today shows an increasing number of firms moving toward vertical disintegration (Harland, 1996; Slack and Lewis, 2002). Lehtinen (1999) argues that companies are re-organizing their value chain, focusing on core activities to achieve and maintain long-term competitive advantage, and outsourcing all other activities. Outsourcing may promise cost and scale advantages, flexibility and access to specialist knowledge. However, outsourcing also poses great challenges in terms of ensuring control, delivery dependability and quality. Furthermore, once a process is outsourced it might be difficult to bring it back in-house. Embleton and Wright (1998) propose keys to successful outsourcing, which include: strategic analysis, selecting providers and managing the relationships.

The decisions to do or buy are influenced primarily by the firm's justification on the performance trade-offs implied by the decisions. However, there are other factors that companies need to consider when deciding if outsourcing an activity is a sensible option. According to Slack et al. (2004), a company is unlikely to outsource if: 1) the activities have long-term strategic importance to their operation or could improve their performance and 2) the company has specialised skills or knowledge in specific activities or it performs better than any potential supplier.

Fine et al. (2002) propose additional factors in assessing activities to outsource or keep in house. They propose a Strategic Value Assessment Model (SVMA), in addition to the traditional Economic Value Adding Analysis, that incorporates qualitative components (customer importance, technology clock speed, competitive position, availability of capable suppliers and product architecture) to the evaluation and decision making process of value chain analyses. This model allows them to classify value chain assets on the basis of both strategic and economic analyses, as assets that should be *kept in-house,* *leveraged, outsourced* or *harvested.* Elements of the value chain that have both high economic and strategic value are likely to be *kept in house.* On the other hand, elements that have both low economic and strategic value are likely to be *outsourced.* Elements that have high economic value but low strategic value are candidate to be *harvested,* while elements that have high strategic value but low economic value should be *leveraged.* Based on this classification they define a target (ideal) value chain configuration and compare the existing posture with the target position.

2.3.4.2 Supply chain relationships

According to Harland (1996), there is an evolving body of research that defines and discusses supply chain management as an intermediate type of relationships within a spectrum that range from a vertical integration to pure market.

Slack et al. (2004) argue that the type of inter-firm contact can be categorised based on:

- The structure of the market relationships in terms of the number of supply relationships used by an operation.
- The closeness of the relationships, ranging from transactional or 'arm-length' relationships at one extreme to close relationships or 'partnerships' at the other extreme.

Based on the above criteria, Slack et al. (2004) identify various possible supply relationships. The traditional or pure market is a type of relationships that is primarily justifiable when there are many alternative suppliers and the costs of moving between suppliers are low. In this type of relationship, a company purchases goods and services from suppliers that satisfy their objectives every time. This type of supply relationship is characterised by short-term relationship and minimum information sharing.

Slack et al. (2004) highlight further that firms today are reducing the number of their suppliers. At the same time, there is an increasing number of organisations attempting to develop 'partnerships' with their suppliers and customers. Lehtinen's (2002) investigation on Finnish subcontractor manufacturers in the past decade shows that there has been a clear shift towards long-term, commitment-based supplier-customer relationships among manufacturers.

Partnerships attempt to achieve the closeness and co-ordination efficiencies of vertical integration without the need for firms to own the asset that supplies them. Ellram (1995) defines partnership as an on going relationship between two organisations which involves a commitment over an extended time period and a mutual sharing of the benefits and risks associated with the relationships. Slack et al. (2004) propose that partnerships are influenced by a number of factors including: trust, long-term expectations, few relationships, sharing success, joint programmes such as joint learning, co-ordination of activities and problem solving, information transparency and multiple point of contacts. Wisner et al. (2004) add the need for commitment and top management support, change management, understanding suppliers capabilities and core competencies, performance metrics and continuous improvement as important factors for successful partnerships.

2.3.5 Important issues in supply chain management

While the previous two sections addressed the strategic aspects of supply chain management, a lot of research in SCM also addressed the problems in planning, performing and controlling supply chain operations. The issues commonly encountered in supply chain operation are information distortion and uncertainties associated with demand and supply.

2.3.5.1 The Bullwhip effect

Information distortion from one player to another in a supply chain has been recognised as an important issue in managing a supply chain. A manufacturer often receives order information from the immediate downstream channel without knowing the demand pattern coming from the end customers. The immediate players such as retailers and distributors often transform the customer demand, which is quite stable at the end customer, into volatile and fluctuated orders. As a consequence, it is often the case that the further upstream along the supply chain, the higher fluctuations are the demand or order pattern. Such a phenomenon has been observed by Jay Forrester in 1960's through his industrial dynamic studies and now is widely known as the **bullwhip effect** (Lee, et al., 1997; Metters, 1997, Fransoo & Wouters, 2000). Lee et al. (1997), for example, observe the amplification of a relatively stable pampers demand at the end customers into a large swing of orders at P & G, the producer of this product. The authors identify four major causes of the bullwhip effect: demand forecast updating, order batching, price fluctuation, and rationing & shortage gaming.

Research on the bullwhip effect has been conducted quite extensively recently. Metters (1997) presented experimental results that show the impact of the bullwhip effect on supply chain profitability. Fransoo & Wouters (2000) discussed measurement issues of the bullwhip effect. They conjectured that the bullwhip effect can be measured based on the ratio between the coefficient of variation (CV) of the demand coming from a downstream player to the CV of orders sent to the upstream player.

In general, the solutions to the bullwhip effect should be in line with the causes. Lee et al. (1997) developed a framework for supply chain co-ordination initiatives to deal with bullwhip effect. The framework includes three general counteracts proposed by the authors: **information sharing, channel alignment**, and **operational efficiency**. In relation to operational efficiency, for example, a company can reduce the bullwhip effect by mitigating price fluctuation with an initiative called every day low price. By this initiative, the manufacturer can reduce the incentives for retailers forward buying. On the other hand, to obtain better demand transparency from the end customers, the manufacturer may have to initiate the use of point-of-sale (POS) data or other means of transferring data such as web-based technology or EDI. Machuca & Barajas (2004) find that the comprehensive use of EDI results in substantial reduction of the bullwhip effect and in the supply chain costs.

2.3.5.2 Matching supply chain strategies with supply and demand uncertainty

Another main issue in supply chain management deals with the issue of uncertainties. There are many sources of uncertainties in a supply chain including supplier lead-time and delivery performance, quality of incoming materials, manufacturing process time, transit time and demand (Lee and Billington, 1992; Davis, 1993). Lee and Billington (1992) claim that one of the potential pitfalls in managing supply chains is failing to understand the likelihood and the magnitude of impact of these uncertainties. As a result, many authors propose the importance of devising supply chain strategies that match the uncertainties inherent in a supply chain. Fisher (1997) proposes that the supply chain strategy has to match the level of demand uncertainty of the product. Lee (2002) extends Fisher's framework to include supply uncertainties.

Fisher (1997) suggests that based on their demand patterns, products can be classified into two classes: primarily functional or primarily innovative. Products are classified as functional if they satisfy basic needs that do not change much over a period. As a result these types of product have stable, predictable demand and long product life cycles. However, the stability provokes competition that leads to lower profit margins. Innovative products have high innovation or fashion content, and therefore tend to have a higher profit margin. However, innovative products have a short life cycle, which results in highly unpredictable demand. Lee (2002) suggests that functional products usually have less product variety compared to innovative products, where variety is introduced due to the fashion-oriented nature of the product or the rapid introduction of new product options due to product technology advancements.

Lee (2002) argues that recognising the uncertainties revolving around the supply side is also important in devising the right supply strategy. Supply can be characterised as stable if the manufacturing process and the underlying technology are mature and the supply base is well established. An 'evolving' supply process is one where the manufacturing process and the underlying technology are still under early development and are rapidly changing. As a result, an evolving supply base might be limited in both size and experience.

Lee (2002) proposed a framework to align supply strategies with the different levels of demand and supply uncertainty. Figure 2.3 illustrates four different strategies proposed by Lee (2002) to cope with different nature of demand and supply uncertainties of different products. These strategies are:

1. *Efficient supply chains*: when companies have predictable demand patterns and a stable supply process, they should aim at improving supply chain efficiency to provide the lowest possible costs for their customers.
2. *Risk-hedging supply cha*ins: when the supply processes are still evolving causing uncertainties in the yield, process reliability, supply source and lead time, companies should attempt to prevent such uncertainties from ultimately affecting demand fulfilment. Companies should establish "risk-hedging" strategy aimed at pooling and sharing resources in a supply chain so that the risks in supply disruption can also be shared..

3. *Responsive supply chains*: when demand is highly unpredictable, companies should develop "responsive" strategy. This strategy aimed at being responsive and flexible to the changes and diversity of customer needs.

4. *Agile supply chains*: companies with innovative products and unstable supply processes should establish "agile" supply chains. These supply chains utilise the combination of "responsive" and "risk-hedging" strategies. The strategies aimed at being responsive and flexible to customer needs, while attempting to hedge the risks of supply shortages or disruption by pooling inventory or other capacity resources.

Supply uncertainty	Demand uncertainty: Low (Functional products)	Demand uncertainty: High (Innovative products)
Low (Stable process)	Efficient supply chains	Responsive supply chains
High (Evolving process)	Risk-hedging supply chains	Agile supply chains

Figure 2.3 Matched supply chain strategy with supply and demand uncertainty (source Lee, 2002)

2.3.6 Literature on international supply chains

In today's business environment, the international factor can be considered as a common characteristic of a supply chain (Akkermans, 1999). International supply chain refers to a network of suppliers and manufacturers in which various value adding activities comprising a finished product are dispersed geographically in a number of countries (Levy, 1997).

The challenges in managing international supply chains have been addressed by several authors. One of the primary challenges in managing international supply chains highlighted by many authors is difficulty in co-ordination (Lee and Billington, 1992) or integration of activities (Wisner et al., 2004, p.17).

Houlihan (1987) has pointed out that international supply chains face greater complexity in integrating systems, data flows, functional objectives and national approach. As a consequence, the possibility and impacts of distortion of information and data as they flow through decision processes in partitioned systems and organisations - the effect well known as the Bullwhip effect - are greater in the international supply chain. He noted further that in the context of global supply chain "...the further a company is from the end user of its products the greater are the swings in demand it experiences".

The problems of integration and functional separation are also highlighted by Meijboom (1989). Meijboom (1999) investigates whether the basic supply chain principles that include a high degree of integration and simplification of basic chain structure - through proper placement of decoupling point - still apply in the context of international operations. To address the problem he conducted an exploratory case study in an internationally operating Dutch company producing children's wear. Results from the case study were used to evaluate the configuration and co-ordination aspects of the company and justify the effects of international operations on the basic supply chain principles. Based on the empirical study, Meijboom propose several points:

- The presence of documents related to the international goods movement results in additional flows that complicate the co-ordination.
- Functional splitting i.e. when subsequent stages in the chain are controlled by different functions or geographic separations found in the international operations *challenges the integration and simplification of supply chain.*

Levy (1995) work was driven by the general premise that a thorough understanding of the costs generated by geographically dispersing activities in the value chain and the evaluation of whether these cost exceed the benefits are important. Levy's study is based on the international value chain of CCT, a personal computer manufacturer that had three manufacturing sites in California, close to corporate headquarter, one in Ireland and one in Singapore. Levy develops a simulation model to investigate the impact of disruptions - related to demand fluctuation, production problems and undependable suppliers - on two measures of the supply chain performance i.e. demand fulfilment and inventory level. As shown in table 2.2, Levy investigate four configurations, in which costs and lead times for CCT's products sourced from slow and responsive Singapore suppliers were compared with those for similar products sourced locally (California) for the US market.

The simulation study found several important points:

1. Demand instability raises the proportion of unfulfilled demand for each configuration. However, it has bigger impact on configuration with longer lead-times (Singapore).

2. Disruption on internal production and supplier deliveries both reduced demand fulfilment and increased inventory level but to a much lesser degree than demand variations. Production disruption in particular has a very little impact on the supply chain, which Levy noted as interesting because the literature tends to point to unstable production and technology rather than demand as factors that hinder international sourcing.

Table 2.2 Levy (1995) simulation of international supply chains

Parameters	Characteristics	
Configuration	**USA Responsive** (finish in 1 month)	**Singapore Responsive** (finish in 1 month + shipping time)
	USA Slow (finish in 2 month)	**Singapore Slow** (finish in 2 month + shipping time)
Input	❑ Level of disruptions affecting demand, supplier deliveries, production ❑ Target levels of systems & component inventories 2 weeks sales for finished goods (not included inventories on transit) 1 week production for components ❑ Lead times for finished goods and for vendors	
Output	❑ Levels of the system and component inventories ❑ Levels of demand fulfilment	
Variables	❑ Monthly demand: previous month + % change (normal, mean zero). Demand instability was the standard deviation of this variable ❑ Production: Production plan - % (exponential, mean represented the level of production instability) ❑ Supplier delivery: Amount of order – random distributed percentage	

Levy (1997) continued his work in CCT by examining the implementation of lean production in an international value chain. His study indicates that lean production - which entails JIT delivery, low inventories and close co-ordination with suppliers and customers - is indeed difficult and expensive to implement in an international supply chain. He argues that in CCT's supply chain, long distances between manufacturer and supplier create longer lead times and consequently increase the amount of inventories in the supply chain. This has made just-in-time delivery impossible. He also finds that distance relates to forecast accuracy in two ways:

1. Due to long shipping time from an offshore manufacturer, the corporate headquarters need to arrange production schedules and orders to the vendors one or two months earlier based on sales forecast further into the future - which in this case were found to be less accurate.
2. Distance also affected the accuracy of sales forecasting by impairing communication. Levy's research found that the accuracy of sales forecasts, over the same time period, was lower for countries remote from the corporate marketing and production scheduling.

However, Levy (1997) also suggests that Design for Manufacture and reduction of defect levels - two key elements of lean production - could facilitate globalisation by stabilising the supply chain.

2.4 Literature on product variety

The number of different products on offer in the marketplace today has increased significantly (MacCarthy, 2001; Fisher et al., 1999). Fisher et al. (1994) states that due to global competition, faster product development and increasingly more flexible manufacturing systems, a great number and variety of products are offered in today's market ranging from toys to power tools and computers.

Based on several marketing reports, Thonemann and Bradley (2002) highlight that the number of new products introduced in the packaged-goods industry has doubled from 12,000 in 1986 to 24,000 in 1996, and the number of products available in large supermarkets has increased from the order of 1000 in the 1950s to 30,000 in a modern supermarket.

As the trend of product variety is increasingly recognised, a lot of studies are carried out to investigate the merit and disadvantages of offering a high variety of products. Some of the important literature addressing this issue is summarised in table 2.3.

Table 2.3 Summary of product variety literature

Author	Description of the literature	Results or proposition
Impact of variety on costs and productivity of a single manufacturing firm		
Lancaster (1990)	Conceptual development of the impact of firm's product variety strategy	• Broader product line can increase the overall demand • A broad product line may increase production costs, inventory costs and add complexity in the assembly process • Product line decision is influenced by strategic orientation
Kekre & Srinivasan (1990)	Investigate the market benefits and cost disadvantages of broader product lines using a marketing database	• Broader product lines could results in significant market benefits • No empirical evidence to support a common belief that product variety increases production costs
Foster & Gupta (1990)	Investigate manufacturing overhead cost drivers in an electronics firm	Only limited correlation is found between manufacturing overhead costs and complexity-based cost drivers
Anderson (1995)	Investigates the relationship between variable manufacturing overhead costs and the measures of product variety in three textile plants of a firm	• Increase in manufacturing overhead costs is influenced by the increase in the number and severity of set-ups • The cost of product mix heterogeneity declines with the experience of producing a heterogeneous product mix
MacDuffie et al. (1996)	Investigate the impact of product variety on total labour productivity and customer-perceived product quality using data from the automotive industry	Different types of product variety have varying impacts on labour productivity: • Model mix complexity has no significant association with labour productivity • Mean optional content has significant positive relation to labour productivity • More variability in options per vehicle results in higher productivity
Fisher & Ittner (1999)	Investigate the impact of product variety on an auto assembly performance	• Option variability results in higher overhead hours, rework, inventory and the excess capacity assigned to a workstation to buffer against variability • Option variability does not have a significant impact to direct labour hours when labour slack is provided
Impact of variety on lead-time and responsiveness		
McCutcheon et al. (1994)	Conceptual development	• Assert that firms in many industries are facing customisation and responsiveness squeeze, which means that neither make-to-stock nor make-to-order is suitable • Firms in such situation may benefit from build-to-order strategy
Thonnemann and Bradley (2002)	Investigate data for six product lines of a hard-drive manufacturer	Average lead-time for product lines with high product variety is longer than the average lead-time of product lines with low variety

Table 2.3 Summary of product variety literature (continued)

Gupta & Srinivasan (1998)	Develop mathematical model to investigate the impact of product proliferation on firms responsiveness (average work-in-process inventory)	Increase in product variety results in decreasing expected average work-in-process (WIP)
Product variety and demand characteristics		
Fisher et al. (1994)	Empirical study in a clothing company	• Argue that as product proliferate, it would be difficult for supply chain members to predict how aggregate demand will be distributed across all the SKUs
Product variety, complexity and co-ordination		
Fisher et al (1995)	Conduct a field study to investigate the impact of product variety on transactions that drive overhead cost	• Greater variety results in increases in the overhead • Part variety raises production costs and coefficient variation in demand for a particular part
Milgate (2001)	Conceptual development	Argues that increase product variety increases overall supply chain complexities
Child et al (1991)	Conceptual development	Assert that complexity costs range from 10 – 40% of total costs
Impact of product variety on supply chain performance		
Randall & Ulrich (2001)	Investigate the relationship between product variety, supply chain structure and firm performance based on data from bicycle industry	There is a coherent way to match variety with supply chain structure: • Production-dominant variety is positively associated with scale efficient and distant production • Market-mediation dominant variety is positively associated with scale-inefficient and local production • Firms that match the types of product variety with the supply chain structure perform better compared to those fail to match variety and supply chain structure
Thonemann & Bradley (2002)	Develop a mathematical model to analyse the impact of product variety on the performance of a supply chain with a single manufacturer and multiple retailers	Expected replenishment lead-time and the retailer's costs are concave increasing in product variety

A great deal of work has been dedicated to investigate the impact of product variety on the performance of a single manufacturing company in terms of **costs** and **productivity**. However, there are also a number of studies that investigate the impact of product variety on firm's **lead-time** and **responsiveness**. While many works on product variety investigate its impact on manufacturing, product variety has also been linked to other aspects of value chain management. Several authors relate product variety to difficulty in demand management, complexity and co-ordination of value chain activities. Finally, investigation has been conducted by several authors on the impact of product variety on supply chain performance. Description on each stream of literature is provided in the following sub-sections.

2.4.1 The impact of product variety on single manufacturing company performance

Product variety has long been considered as one of the important characteristics of operations that define a certain company competitive strategy (Slack et al., 2004, p. 21 & 23). The breadth of product to offer is a strategic decision that may evoke different responses from marketing and manufacturing (Kekre and Srinivasan, 1990; Crittenden et al., 1993; Gupta and Srinivasan, 1998). It is argued that manufacturing prefers minimal disruptions on process and thus discourages product proliferation. On the other hand, marketing aims to satisfy diverging customer needs and eventually gain increased market share, and thus emphasises a broader product line (Kekre and Srinivasan, 1990).

Product variety has also been studied from marketing perspective. For example, Lancaster (1990) identifies three effects of firms' product variety strategy in the context of marketing:

- *On the demand side,* many authors have suggested that broader product line can increase the overall demand faced by the firm, as it allows a firm to satisfy the needs and wants of heterogeneous consumers. Kekre and Srinivasan (1990) investigate the market benefits and cost disadvantages of broader product lines using the Profit Impact of Marketing Strategies

(PIMS) database. They find that significant market benefits could accrue from broader product lines.

- *On the supply side*, a broad product line is associated with increasing firm's per unit production costs when scale economies are present, adding design and inventory holding costs, and complexity in the assembly process
- The decision on product line is also influenced by *external strategic considerations* such as deterring market entry, defensive strategies against competitors or to enhance a firm's reputation.

Many authors have investigated the impact of product variety on production or manufacturing. Kekre and Srinivasan (1990) state that there is no empirical evidence to support a common belief that product variety increases production costs. Foster and Gupta (1990) study manufacturing overhead cost drivers in an electronics firm. They also observe that there is only limited correlation between manufacturing overhead costs and complexity based cost drivers such as total number of parts, number of suppliers and breadth of product line.

Anderson (1995) argues that the absence of a systemic relation between product variety and **Manufacturing Overhead Cost (MOHC)** might be caused by limitations of the variables typically used to capture product variety. Several measures or proxies of product variety used in the previous studies, including the number of products produced, number of engineering changes and number of product introductions fail to distinguish similarities and differences among products. In order to fill this gap, Anderson (1995) uses a group technology method, which captures similarities and differences across products, to measure **Product Mix Heterogeneity (PMH)**. In this way, the measures of PMH are better linked than simple proxies to the underlying theories of economies of scope, focused factories and activity based costing that first motivated estimation of MOHC.

Anderson (1995) uses regression analysis to examine the relationship between variable MOHC and the measures of PMH in three textile-weaving plants of a single firm. Each plant specialises in producing textile fabrics from different types of raw material. One plant also acts as a 'swing' plant, used to balance capacity utilisation of the three plants. PMH is captured in two forms: 1) sequential production of different products on a machine and 2) simultaneous production of different products on many parallel machines. The fixed effects of sequential PMH are measured by the number of major and minor set-ups. Results from this study indicate that increased MOHC is associated with the increase in the number and severity of set-ups. Furthermore, increasing heterogeneity in process specifications and quality standard of a plant's product mix are also significantly related to increased MOHC.

The most important finding from Anderson (1995) is that the cost of PMH declines with the experience of producing a heterogeneous product mix. This is found in two relationships:

1. A plant that has the greatest experience doing major set-ups, has the lowest cost of major set-ups; while a plant that has the greatest experience doing minor set-ups, has the lowest cost of minor set-ups

2. Raw material variety increased direct and indirect labour costs for to focused plant, but had no impact on costs of the plant that by design faced the highest level of raw material variety. This implies that experience to produce fabrics from a variety of raw materials may decrease the costs of raw material variety.

This evidence suggests *variety-based learning* i.e. that costs associated with sequential PMH are mitigated by experience changing between heterogeneous products. This finding challenges the focus factory strategy, suggesting instead strategies for accelerating variety-based learning to achieve complete manufacturing flexibility.

The automotive industry is one among many industries facing increasing pressure to produce more product variety. The automotive industry, pioneered by Henry Ford's famous offer of "any colour as long as it's black", have previously exploited a strategy of producing the right level and type of product variety (Fisher and Ittner, 1999). However, as the customer needs change rapidly, firms can no longer make profits by producing large volumes of a standardised product (MacDuffie et al., 1996). The industry has seen steady increases in the amount of product variety initiated by General Motor's strategy of segmentation by value and price, and more recently driven by European and Japanese manufacturer that differentiate their product based on size and popular niche cars (Fisher and Ittner, 1999).

These facts have drawn the attention of many researchers to investigate the issue of product variety in the automotive industry. MacDuffie et al. (1996)

examine the effects of product variety on total labour productivity and consumer-perceived product quality using data from the International Motor Vehicle Program's (MIT) study of 70 assembly plants worldwide. They use the term 'variety' to refer to company choices about the breadth and depth of different product lines i.e. product market strategy, and 'complexity' to refer to the dimension of the manufacturing task that results from the product strategy.

Three dimensions are examined: fundamental, peripheral, and intermediate levels of variety. The three levels of product variety are captured in several different measures of product complexity as follows:

1. Model Mix Complexity measured fundamental variety and is based on the number of different platforms, body styles and models, scaled by the number of different body shops and assembly lines in each plant.
2. Parts Complexity results from an intermediate level of product variety that is partially driven by consumer choice e.g. exterior colour, the combinations of the engines and transmissions, but also reflects the impact of higher variety on product design (e.g. the number of main wire harnesses, the commonality of parts across models) and the supply system (e.g. the number of assembly area part numbers, the number of suppliers to the assembly area).
3. Option Content is often referred to as peripheral variety because the variations are independent of the core design. Option content is calculated from the percentage of vehicles built with various options aggregated across all models in a plant.

4. Option Variability also captures peripheral variety. While option content reflects the overall level of installed options, option variability captures the variance in option content within each model and across models manufactured in the plant.

This study reveals varying impacts of different types of product variety on labour productivity. As expected, the **mean optional content** per vehicle has a significant positive relation to labour productivity i.e. higher option content led to more hours per car. However, **differences in model mix,** e.g. whether it is two-door or four-door cars, had no significant association with labour content per car. The authors argue that the minimal effect of model mix complexity on productivity might be due to the fact that plants have appropriate tooling in the body shop for whatever level of model mix they produce. In this situation switching between these body styles caused little penalty and it is essentially infeasible to produce any style outside this mix.

Surprisingly, **more variability in options per vehicle** leads to higher productivity, in contrast to the expectation that higher variety should lead to more hours per car, i.e. lower productivity. The authors argue that this might be because plants with very high option variability operate on a different and more flexible production frontier, and thus are less affected by variability than more inflexible plants.

The study also reveals that **parts complexity** is found to have a persistent and statistically significant impact on productivity. While parts complexity is less frequently examined compared to fundamental or peripheral variety, it is arguably most problematic for manufacturer. Fisher et al. (1995) conduct a field study in automotive plants and find that greater part variety means lower volume per part. This not only raises production costs, but also increases the coefficient of variation in demand for a particular part, hence requiring greater safety stocks and/or leading to increased risks of stock outs.

Fisher and Ittner (1999) use data from General Motors' Wilmington, Delaware Plant to examine the impact of product variety on auto assembly plant performance. In addition, they also conduct simulation analysis of a more general auto assembly line. They attempt to investigate which dimensions of product variety affect measures of manufacturing performance such as labour productivity, rework and inventory.

The empirical analyses conducted by Fisher and Ittner (1999) indicate that in mixed model assembly operations, variability in product mix may be a better indicator of product variety than measures such as the number of products or number of parts commonly used in research studies and activity-based costing systems. The empirical study also found that option variability increases overhead hours, rework, inventory and the excess labour capacity assigned to a workstation to buffer against variability. However, option variability does not significantly impact direct labour hours when labour slack is provided to shield assembly workers from the adverse affects of product variety.

The simulation study conducted by Fisher and Ittner (1999) indicates that the use of direct labour slack is an optimal response to increased option variability. It also confirms that the level of option variety has an insignificant impact on direct labour once the line has been optimally buffered against process time variability with excess capacity. The simulation analyses also shows that bundling options can reduce the amount of buffer capacity required. This finding supports the industry's attempts to reduce costs by bundling options into a few packages.

2.4.2 Product variety, lead-time and responsiveness

The works on product variety addressed previously focus on investigating the impact of product variety on manufacturing performance, primarily in terms of costs and productivity. The business environment today has become more customer-focused, and as a result many companies increasingly recognised the importance of responsiveness to customer needs (Kritchanchai, 1999). Several authors relate product variety with other aspect of manufacturing performance including manufacturing lead-time and responsiveness. Stalk (1988) highlights that the success of Japanese manufacturers in offering wide range of product variety is due to their ability to execute their processes much faster. He argues that "strategies based on the cycle of flexible manufacturing, rapid response, expanding variety and increasing innovation are time based".

McCutcheon et al. (1994) assert that firms in many industries are facing "customisation and responsiveness squeeze" as customers demand both greater product variety and reduced delivery times than previously. The trend is characterised by the need to deliver differentiated products in considerably less time than it takes to make them. When the customer is willing to wait for customized product, firms can respond with a make-to-order approach. However, the pressure for fast response and customisation means that neither make-to-stock nor make-to-order is suitable. The problem becomes more complex if product is differentiated early in the production process. McCutcheon et al. (1994) argue that firms may cope with this situation by applying several approaches: altering process design, altering product design, managing demand and supply, using slack resources and build-to-forecast strategy.

Thonemann and Bradley (2002) provide insights on the impact of product variety on manufacturing lead-time. They investigate data for six product lines of an actual hard-drive manufacturer and found that the average lead-time for product lines with high product variety is typically greater than the average lead-time for product lines with low product variety. This eventually results in increased retailers' cost, as longer average lead-time requires the retailers to hold more inventories.

Gupta and Srinivasan (1998) investigate the impact of product proliferation on a firm's responsiveness in term of average work-in-process inventory (backlog). Gupta and Srinivasan describe their production facility as a make-to-order system with a single bottleneck operation, and model it as a single server queuing system with N customer (product) classes. The facility processes requests for the same type of item continuously until there is no pending demand for that item in order to minimise set-up. In conducting the mathematical analysis, they assume that the overall capacity utilisation remains constant. Furthermore, a symmetric production system is considered i.e. symmetry is assumed to exist before as well as after any change in the number of product types produced by the system. Based on these conditions they demonstrate that an increase in product variety leads to a decreasing expected average work-in-process (WIP) of a product and over all products, thus contradicting a common belief that increasing product variety worsens firm's responsiveness.

2.4.3 Product variety and other value chain activities

While the previous works address the 'direct' impact of product variety on the production and manufacturing performance, many authors also assert the potential impact of product variety on other aspects in the value chain.

2.4.3.1 Product variety and demand characteristics

Fisher et al. (1994) assess the potential impact of greater levels of product variety on the predictability of demand using data from a clothing company. They argue that as products proliferate, demand is divided over a growing number of stock-keeping units (SKU). This implies that although the manufacturers and retailers can forecast aggregate demand figures with some certainty, it is difficult to predict how the aggregate demand will be distributed across all the SKUs. According to Randall and Ulrich (2001) demand uncertainty due to variety results in *market mediation costs*, which include the inventory holding cost, product mark-down costs occurring when supply exceeds demand and the cost of lost sales when demand exceeds supply.

2.4.3.2 Product variety, complexity and co-ordination

Product variety is also associated with complexity and co-ordination of activities in the value chain. A field study conducted by Fisher et al. (1995) find that product variety results in increases in the overhead because more efforts need to be dedicated to create demand forecasts, manage greater inventory and material handling, dealing with more complex scheduling and task assignment and more frequent engineering changes.

Milgate (2001) states that "while increased product variety undoubtedly increases overall supply chain complexity, the breadth of a firm's product portfolio is directly associated with the number of tasks and difficulty of co-ordination". He asserts that product variety might not be associated fundamentally with technical complexity and inter-connectivity of a product. He exemplifies that offering a product in different colours or sizes does not make the product more complex. However, it introduces complexity in co-ordinating the production of such a variety of products.

Child et al. (1991) assert that complexity costs are real and often significant. They argue that complexity costs range from 10 – 40% of total costs depending on the number of items (including materials, parts, packages, etc.), tasks (e.g. making design changes, preparing production schedule, etc.), flows (production sites and distribution channel), and inventories (including raw material, work in progress and finished goods).

2.4.4 The impact of product variety on supply chain performance

More recently, there is a quantity of research that investigates the issue of product variety in the context of supply chains. Randall and Ulrich (2001) examine the relationship between product variety, supply chain structure and a firm's performance using data from the U.S bicycle industry. Product variety is defined as the number of different versions of a product offered by a firm at a single point in time. They adopt a common practice in the consumer product literature, where complete products are modelled as bundles of consumer attributes. Variety within a product line arises by varying the values of attributes from one product to another.

They argue that product variety incurs two types of costs within supply chains: production cost and market mediation cost. Production costs include direct materials, labour, manufacturing overhead and process technology investment. As noted previously, market mediation costs are associated with inventory holding cost, product markdown cost and the cost of lost sales.

Randall and Ulrich argue that different types of variety have different relative impacts on production and market mediation costs, depending on the attribute causing the variety. Some attributes cause high production cost, while other types of variety might incur high market mediation costs. Based on this notion, they differentiate variety as production-dominant variety and mediation-dominant variety. Variety is production-dominant if it incurs production costs that outweigh the market mediation cost e.g. variation in body styles of an automobile requires a great tooling investment. On the contrary, variety incurring market-mediation costs that outweigh production cost is referred to as market-dominant variety. An example of market-mediation variety is variation in trim colours of an automobile, as the impact of additional colours on production is marginal relative to the increase in inventory and stock-out costs.

According to Randall and Ulrich (2001), the structure of the supply chain also affects the magnitude of production and market mediation costs. They characterise the supply chain structure along two dimensions commonly used in operations literature: 1) the distance of production facilities from a target market (distance), and 2) the degree to which production facilities reach minimum efficient scale (scale efficiency). In order to achieve production cost advantages through economies of scale, a firm might attempt to pool (aggregate) production volume of different geographic markets into one facility. Aggregating production into a central facility often forced geographic distance from regional markets creating longer replenishment time and forecast horizon. This eventually increases the exposure to demand uncertainty and increases market mediation costs. To minimise market mediation costs, a firm has incentive to build plants locally at a cost of reduced scale.

Based on the above concepts, Randall and Ulrich state that there is a coherent way to match product variety with supply chain structure. Their empirical study of the bicycle industry found that production-dominant variety is positively associated with scale-efficient and distant production, while market-mediation dominant variety is positively associated with scale-inefficient and local production. The results also suggest that firms that correctly match the types of product variety on offer with the supply chain structure perform better compared to those that fail to match such choices.

Thonemann and Bradley (2002) present a stylised model for analysing the effect of product variety on performance of a supply chain with a single manufacturer and multiple retailers. The manufacturer produces multiple products on a shared resource with limited capacity and the effect of changeovers on supply-chain cost is due primarily to set-up time rather than set-up cost.

The authors challenge previous works that: 1) disregard the effect of product variety on lead-time or 2) assume that standard results for a perfectly flexible system applies, which lead to a proposition that cost increases proportionally to the square root of product variety. They show that the expected replenishment lead-time and the retailer's costs are concave, increasing in product variety. This implies that if set-up times are significant, the effect of product variety on cost is substantially greater than that suggested by risk-pooling literature for perfectly flexible manufacturing processes. They suggest that the underestimation of the potential savings or potential cost increases leads companies to offer product variety that is greater than optimal.

2.4.5 Product variety and mass customization

In recent years, the notion of producing a wide breadth of products to satisfy differentiating customer needs is developed further with the introduction of the mass customization concept. The underlying goal of mass customization is to produce customized product with the level of efficiency and costs of mass-produced products (Pine, 1993; Hart, 1995). There has been a growing number of works in the area of mass customization aiming to develop operation modes for mass customization (MacCarthy et al., 2003); developing product family architecture for mass customization (Jiao and Tseng, 1999); and describing companies' success stories in applying the concept (Feitzenger and Lee, 1997; Kotha, 1996). Mass customization covers a broader area than product variety management. However, some of the profound strategies such as modular product build strategies and postponement are applicable in both areas. Our study focuses on these overlapping areas.

2.4.6 Strategies to mitigate the negative impact of product variety

While sections 2.4.1 – 2.4.4 focus on the literature investigating the impact of variety, much has been written in the literature on how to manage and mitigate the negative impacts of product variety.

2.4.6.1 Framework of managing product variety

Ulrich et al. (1998) propose several key points for managing product variety that apply to most industries:

1. Variety management introduces challenges for firms at a strategic and tactical level. The decisions at a strategic level aim to create an effective

variety delivery system, including: a) the dimensions of variety offered, b) the nature of the customer interface and distribution channel, c) the degree of vertical integration, d) the process technology, e) the decoupling point in the supply chain, and f) the product architecture.

2. Variety is multidimensional, thus comparison on the level of product variety has to be made along a particular dimension of variety in addition to analysis at the level of end-items.
3. A variety strategy can be evaluated and selected based on several criteria: a) perceived value of variety to the customer, b) competitive distinction of variety, c) the product architecture and production/distribution system choices minimise costs given the chosen dimensions of variety, d) firm's design and operations capabilities, and e) the strategy to exploit the context and resources of the firm such as location, history and relationships.
4. Variety strategies are dynamic, path dependent and context dependent. Changes in product variety strategy are limited by an existing firm's resources and capabilities and changes in the competitive context.
5. No single variety strategy dominates. An effective variety strategy is a coherent set of marketing, design and manufacturing decisions, and thus no single variety strategy will be appropriate in all settings.

Many authors emphasise the importance of recognising the value of variety to the customers as an important step of managing product variety. Fisher et al. (1995) argue that companies need a market strategy to minimize product variety that customers do not want. This would include: 1) close interaction with customers to ensure that the new product truly reflects customer needs and preferences, and 2) eliminating products that are no longer beneficial. Child et al. (1999) suggest that a company must assess the level of variety that customers will still find attractive to avoid customer confusion and withdrawal from the purchase decision. Kahn (1998) provides a summary of research on consumer behaviour focusing on understanding why consumers seek variety in their own choices over time. Companies should develop strategies to identify the optimal choice for their customers without confusing the customers with information overload. MacCarthy et al. (2002) argue that identification of the *product attribute(s) that represent the greatest perceived value to the customer* i.e. Key Value Attributes (KVA) can be used to distinguish useful variety from useless variety.

Da Silveira's (1998) framework of variety management begins with understanding the strategic importance of product variety determined by different factors including level of customisation, level of customer requirements and market competition. This is followed by 1) analysis of the gaps between the strategic importance of product variety and companies capabilities to deliver the required variety and 2) the implementation of adaptive and flexibility strategies to close the gaps.

Ramdas (2003) provides a framework for management decisions about product variety. Ramdas argues that the success of a firm's product variety strategy is determined by two main determinants: how firms create variety (variety-creation) and how the firms implement variety (variety-implementation). Key decisions in variety-creation include: 1) dimensions of variety, 2) product architecture, 3) degree of customisation, and 4) timing, whilst key decisions in variety-implementation are: 1) process capabilities, 2) points of variegation, and 3) day-to-day decisions.

Fisher et al. (1999) suggest that the approaches used by companies to cope with product variety can be classified as process based or product based. Process-based strategies aim to provide production and distribution processes with sufficient flexibility to enable them to accommodate a high level of variety at a reasonable cost. Product-based strategies aim for product designs that allow high variety in the marketplace while maintaining a relatively low level of component variety and assembly complexity in the production and distribution system.

2.4.6.2 Process-based strategies

Flexible process design can be achieved through flexible technology, plant configurations based on the principles of cellular manufacturing (McCutcheon et al., 1994) and reductions in changeover times on conventional technology. The merits of a flexible manufacturing system are well documented. Stalk (1988) compared the manufacturing costs associated with volume and variety between a 'traditional' and a 'flexible' factory system. Stalk argues that in a flexible factory system the costs associated with product variety start lower and increase more slowly as variety grows, whilst cost associated with volume remain unchanged. As a result, the optimum cost point occurs at a higher volume and with greater variety compared to the traditional factory. Stalk concludes that a flexible factory offers more variety with lower total costs compared to a traditional factory that still faces severe trade-offs between volume and variety.

Fisher et al. (1995) support the investment in flexible manufacturing capabilities including technology, organisational system and human skills. They argue that combining these flexible capabilities not only offers the ability to make multiple products simultaneously, but also the benefits of reduced changeover costs across product generations, the ability to adjust product mix in uncertain demand, and the ability to use the factory as testing ground for new products and processes. In the absence of perfect manufacturing flexibility, Thonemann and Bradley (2002) propose that reducing set-up times enables a supply chain with high variety to reduce its costs.

2.4.6.3 Product-based strategies

Product-based strategies include modular product, standardisation of materials and component sharing. According to McCutcheon et al. (1994) the best way to achieve product variety and speed is through modular product configuration. Starr (1965) defines a modular production as a capacity to design and manufacture parts, which can be combined in maximum number of ways. Ulrich (1995) explains that whilst integral product requires changes to every component to accommodate changes in any functional element, modular product enable changes in each element to be done independently by changing only the corresponding element. Hence, the primary advantage of modularity is due to the fact that changes or improvement on components in a modular system can be done without affecting other parts of the system (Galvin and Morkel, 2001). In this way, companies, such as Honda, Sharp and LEGO can offer a wider combination of end product variety without imposing higher complexity in their operations (Child et al., 1991).

Another example of a product-based strategy is standardisation of materials. Child et al. (1991) describes how several companies benefit from applying standardisation strategy. A summary of these cases is shown in table 2.4.

Table 2.4 Case companies applying standardisation strategy (Adapted from Child et al., 1991)

Company	Standardisation strategy	Result
European consumer goods manufacturer	Standardising the open end of all bottles	Allow the company to use the same highly efficient bottling process with negligible costs for changeovers to different liquids
A Japanese machine tool builder	Standardising the form elements such as hole diameter that designers use for new parts	The manufacturing process uses the same machines, tools and jigs despite different parts. Thus, set up and new product introduction time are eliminated
European electric appliance manufacturer	Standardising some materials to the highest necessary standards of product range and automating process using the materials	Reduced manufacturing workforce and increased productivity

The idea of component sharing is developed on the general notion that families of similar products have similar components. Fisher et al. (1999) propose that component sharing, i.e. using the same version of a component across different products, is increasingly perceived by many companies as a way to offer breadth of end-product variety while maintaining low variety in operations. The main drivers for component sharing are the potential reduction in costs of product development, production investment associated with a new product, as well as system cost such as quality assurance, procurement and spare parts inventory. Fisher et al. (1999) examine component sharing in automotive front brakes that is classified as having a weak influence on product quality. Using an analytical model they found that the number of components to be used for a certain number of products types is increasing in the range of the performance requirement, increasing with the overall production volume of the set of products and decreasing in the magnitude of economies of scale. They also expect more component sharing with increasing variability of volume across different products.

2.4.6.4 Structural-based strategies

As reviewed previously, Randall and Ulrich (2001) argue that firms with matching types of product variety and supply chain structure will be able to mitigate some of the cost trade-offs incurred by product variety. They suggest that firms producing product variety that incur high production cost (fixed investment, manufacturing overhead, etc.) might attempt to pool volume of production into a scale efficient plant, sometimes at a cost of separating the plant further from the market. On the other hand, firms producing variety associated with demand uncertainty might be better off producing close to the market in order to be more responsive, at a cost of reduced scale.

Child et al. (1991) suggest that offering wide variety of product does not necessarily lead to complex configuration and co-ordination. The authors argue that co-ordinating a large number of interdependent plants is very costly.

Thus, in order to avoid complexity of configuration and co-ordination, firms should:

- Reduce the interdependency between plants by dedicating plants and manufacturing departments to a type of finished product and not to a function or process step
- Separate manufacturing facilities for small and large lots
- Design facilities with dedicated, highly flexible production equipment and simple procedure

Thonemann and Bradley's (2002) analyses of a supply chain with a single manufacturer and multiple retailers suggest that changes in the supply chain structure might improve the performance of the supply chain. They argue that if demand is allocated across fewer retailers, demand variability decreases relative to the mean demand over lead-time. This implies that consolidating retailers might reduce cost.

2.4.6.5 Postponement

One of the prominent concepts to cope with product variety that combine the product, process and structural design is postponement. Whang and Lee (1998) define postponement as "delaying the point of product differentiation in a production process". Bowersox and Closs (1996) identify three aspects of postponement:

- Form postponement entails delaying the process that transforms the form and function of products until customer orders have been received

- Time postponement refers to delaying the movement of goods until customer orders have been received
- Place postponement means positioning the inventories in centralized manufacturing or distributions operations

Based on these, Van Hoek (1999) summarises postponed manufacturing as "final processing and manufacturing activities are postponed until customer orders have been received (time postponement) and are performed from central locations in the international supply chain (place postponement) to include customer and country specific characteristics in the finished products..."

Van Hoek (1999) proposes that there are strong inter-relationships among postponement, outsourcing and geographical reconfiguration. He argues that postponing manufacturing activities opens up opportunities for outsourcing these activities to third-party. He also notes that postponement has an obvious relation with the configuration of the supply chain. Postponed manufacturing might entail repositioning of inventory to a central location, repositioning of final manufacturing activities and reconfiguration of the supply structure.

The success stories of Hewlett-Packard in applying postponement strategy to enable fast delivery of a wide variety of end products whilst maintaining low inventory and logistics cost are well documented and widely referred to in the literature (Lee et al. 1993; Feitzenger and Lee, 1997).

2.4.6.6 Management policies

MacDuffie et al.'s (1996) work partially supports the hypothesis that management policies associated with lean production can facilitate the absorption of higher levels of product variety. They argued that lean production policies including Just-in-time inventory systems, work teams, job rotation and extensive training to develop multi-skilled workforce, continuous environment effort and design for manufacture can give a lean production plant the capabilities of handling higher levels of product variety with less adverse impact on total labour productivity than a traditional mass production plant.

2.5 Synthesis of the literature

The review of various streams of literature gave an important background for conducting this study. It also reveals important gaps in the current literature that need to be addressed further. The main contribution and gaps identified from each stream of literature are presented in figure 2.4. As shown in figure 2.4, both the international operations and the general supply chain management literature emphasise the importance of understanding the structure or configuration of network of factories as an initial step to highlight potential management problems. The main aspects that need to be considered in understanding the configuration of an international network of factories are:

- Elements involved in the network
- Location of each element
- The responsibilities of each element
- Activities conducted in-house and contracted out

International operations literature

- Insights on motivation to develop international operations
- Strategic priorities determine the role of plants and task allocated to the plant
- Factors influencing manufacturing configuration
- Empirical evidences on how the real internationally operating companies structure its value chain activities
- Co-ordination of international network of factories

Main contribution:
Insights on important factors influencing configuration and co-ordination of organisations operating internationally

Gaps:

- Focus on MNC network while different types of international engagement/relationship exist
- Less attention on the impact of configuration and co-ordination strategy on the operations and performance of the supply chain

Supply chain literature

- The importance of understanding the supply chain structure i.e. what elements are involved in a supply network and organisations i.e. how elements are linked to one another, type of relationship, information sharing, etc
- Insights on the issues of supply and demand uncertainty in supply chain management

Main contribution:
Insights on the importance of understanding supply and demand uncertainty in managing supply chains

Gap:
Does not specifically pay attention to the impact of product variety

International supply chain literature

- The challenges associated with international supply chain e.g. long lead-time, uncertain delivery, difficulty in integration, etc.
- Linking the configuration with the operations and performance of international supply chains

Main contribution:
Insights on the risks associated with international supply chain

Gap:
Does not specifically pay attention to the impact of product variety

Product variety literature

- The issue of product variety is traditionally being investigated in a single company perspective
- Insights on the impact of product variety on the performance of a single firm or a general supply chain
- Insights on strategies to reduce the negative impact of product variety

Main contribution:
Insights on the impact of product variety on manufacturing or supply chains performance & potential strategies to mitigate the negative impacts of product variety

Gap:
Does not specifically address the issue of product variety in the context of international supply chain management

Overall Gap:
There has not been any work that addresses the relationship between product variety and other factors in managing an international supply chain and investigate the potential impact of these factors on international supply chain performance

Figure 2.4 Contribution and gaps identified in existing literature

Having understood the configuration of the supply network, the next important point emerging from the literature is the co-ordination strategy that is used to integrate the element within the supply network. Co-ordination aspect will include the following issues:

- How the elements involved in the international supply network is linked and integrated
- Flow of materials and information across elements
- Co-ordination mechanism employed across the elements
- The nature of the relationships across elements in the network

Literature in supply chain management emphasizes the importance of applying supply chain strategies that match the supply and demand uncertainty. Challenges and risks associated with managing an international supply chain are also highlighted.

The literature on product variety shows that different companies competing in different industries and producing different types of product are likely to face different product variety related problems. Companies producing technologically complex products such as automobiles appear to view the issue of product variety based on the complexity that different product variants impose on the manufacturing tasks. In investigating the impact of product variety on automotive manufacturers, researchers have used different measures of product variety such as fundamental, intermediate and peripheral (MacDuffie et al., 1996; Fisher and Ittner, 1999).

On the other hand, as noted by Milgate (2001), product variety might not fundamentally correlate with technical complexity and inter-connectivity of a product. Product variety in less complex products can be measured in different ways. Kekre and Srinivasan (1990) used product line breadth approach that simply counts the number of products in the range. Anderson (1995) uses an attribute-based model of product variety in investigating the relationship between costs and product variety in three textile-weaving plants. Similarly, Randall and Ulrich (2001) also measure differences in bicycle products at the product attribute level.

Despite differences in dimensions of product variety used in the literature, works on product variety in most industries highlights the importance of parts and material variety. Furthermore, product variety not only affects the production, but also potentially affects other activities in the supply chain. Many authors highlight the fact that product variety creates challenges in terms of co-ordination within the company and with suppliers. Product variety is also associated with difficulty in forecasting product demand (Fisher et al., 1994; Randall and Ulrich, 2001).

2.6 Gaps in the literature and direction of the study

The current literature provides important insights on the state-of-the-art on the issues to be investigated in this study. A number of gaps are clear. As shown in figure 2.4, the principal limitation in the existing literature is the fact that the issues of product variety and international supply chain management have not been addressed together in the literature. Figure 2.4 also shows the principal limitations for each stream of literature. More detailed gaps identified from each stream of literature are discussed in this section.

Most of the literature on international operations reviewed previously concerned the issues facing companies in industrialised countries and regions. There are needs for empirical studies that span a wider range of countries (Prasad and Babbar, 2000), particularly in developing countries, in order to garner broader insights and develop general theories of international operations management. Furthermore, the international operations literature concentrates on the linkages between Multinational Corporations and their network of foreign subsidiaries (Ferdows, 1989; Martinez and Jarillo, 1991; Harzing, 2001). In reality, there are many other international engagements such as contract manufacturer, joint venture or licensing (Schary and Skjott-Larsen, 1995; Bennett, 2001) that need further investigation. As significant parts of the value chain activities are likely to occur at the subsidiary level, many authors have highlighted the significant role of foreign subsidiaries (Ferdows, 1989; Oliff et al., 1989; Meijboom and Vos, 1997; Birkinshaw and Hood, 2001). However, there have not been many significant studies that address the operational issues faced by foreign subsidiaries.

It is also found that the current international operations literature focuses on the strategic issues of international operations including configuration (Ferdows, 1989; DuBois et al., 1993) or in development of international manufacturing strategy (McGrath & Bequillard, 1989; Martinez and Jarillo, 1991). As argued by Harzing (2000), developing a typology or classification may help reduce the complexity of internationally operating companies into a manageable number of related characteristics, making it easier to understand the functioning of the companies. Meaningful classifications of companies can be used further to address the phenomena that occur in different sample of companies in 'predictive' or 'prescriptive' ways (Harzing, 2000). The literature on classification (Ferdows, 1989; Roth, 1992; Harzing, 2000) so far has laid important foundations in pointing at factors that differentiate one company from another, which can be used to predict other companies' characteristics. However, it has not looked in more detail at how different international networks of factories perform under different configuration and co-ordination so that the classification can be used in more 'prescriptive' ways.

Furthermore, the literature on international operations puts less attention on co-ordination of more operational issues including planning, execution and control of activities within the international network of factories. As suggested by Oliff et al. (1989) very little work is dedicated to investigate the co-ordination of forecasts, production plans, shipping schedules and other information among members of the chain in order to achieve the overall objectives. The current literature mainly provides the conceptual framework to co-ordinate international network of factories (McGrath and Bequillard, 1989; Martinez and Jarillo, 1991). There have not been many significant works that look at the execution of the co-ordination across different international supply networks. Based on the insights on configuration and co-ordination provided by the current literature, further research should try to investigate the performance of international supply networks under a certain configuration and co-ordination (Prasad et al., 2001).

The literature in general supply chain management attempts to find ways to mitigate the impact of demand and supply uncertainty on supply chain performance. There is a need to relate the configuration and co-ordination strategy with other factors in managing international supply chain including supply and demand uncertainty, and demonstrate the potential impact of these factors on performance of international supply chains. Levy (1995) is among very few works that capture the impact of configuration, supply and demand uncertainty on the international supply chain performance. However, his work does not address the issue of product variety and the scope of the study was limited.

Whilst some authors propose the connection of product variety and management of supply chain, works on product variety traditionally look at the impact of product variety from a single manufacturing company's perspective in a certain type of industry. In particular, there has been a great deal of work addressing the issue of product variety in the automotive industry. In reality, product variety is no longer restricted to complex products or costly industrial products, as many product categories such as personal computers, clothes, credit cards etc., are also facing increasing level of product variety (Forza and Salvador, 2002; Ramdas, 2003). Thus, research on product variety in different industries is required.

Many authors attempt to investigate the impact of product variety on manufacturing or production. However, it is evident from the review in section 2.5.2 that different authors use different terminologies, measures and approaches in addressing the issue of product variety, which result in inconclusive and seemingly contradictory views on the impact of product variety on manufacturing performance. In order to avoid further confusion, a clear measure of product variety with clear impact on production or manufacturing is essential. Furthermore, most of the researches in product variety apply statistical analysis to investigate associative relationship between different aspects of variety and performance measure or develop complex mathematical modelling. Ramdas (2003) states the need to apply other established research techniques, including simulation, in the context of variety management. More specifically, a simulation model that demonstrates causal or logical relationships between product variety and performance would provide valuable insights on the management of product variety.

Literature on product variety generally emphasises the potential impacts of product variety on manufacturing productivity and costs. In many industries such as apparel or fast moving consumer goods, the ability to offer a wide breadth of product variants in the shortest time possible is prominent. Thus, more works are needed to investigate the impact of product variety on lead-time or more widely on responsiveness.

Many authors highlight that product variety also poses great challenges associated with material or part management and supply system (MacDuffie et al., 1996; Milgate, 2001). In general, there are still very limited works addressing the issue of product variety in the context of supply chain management. Thonemann and Bradley (2002) and Randall and Ulrich (2001) are among the few works that investigate the impact of increasing product variety on a certain supply chain environment. However, they work on a general supply chain environment that does not specifically capture the international aspects. In today's business environment, as more and more firms produce their products using an international network of suppliers and manufacturers, addressing the issue of product variety in the context of international supply chain management promises fruitful investigation.

Chapter 3
Research Methodology

3.1 Overview of the overall research stages

The previous chapter has reviewed the state-of-the-art of the literature on product variety and international supply chain management. While it is understandable that product variety and international supply chain management are two inter-related problems, the current literature has treated them as two separate issues. This study aims to address this gap by considering inter-relationships between these two issues. In particular, we attempt to answer a number of research questions about managing product variety within the context of international supply networks.

The study will be conducted through both empirical research and simulation modelling. The empirical research is based on interviews with a range of companies, each of which is engaged in international supply networks. In addition to providing general insights on various issues of managing product variety in international supply networks, the empirical study also serves as a basis for developing the simulation model under which more detailed questions are addressed.

Figure 3.1 outlines the general steps of the study. It starts with the identification of the research questions, to be described in section 3.2. The next step is the empirical study. As can be seen from figure 3.1, there are two rounds of the empirical study. More detailed explanation on the stages involved in conducting the empirical study will be presented in section 3.3.

Overall findings obtained from the case companies are analysed following the second empirical study. At the same time, a simulation model is then developed and simulation experiments are conducted. Section 3.4 provides an overview of the simulation study that justifies the use of, and the nature of, the simulation study conducted. Finally, findings from the empirical and simulation studies are synthesised to reach the conclusions.

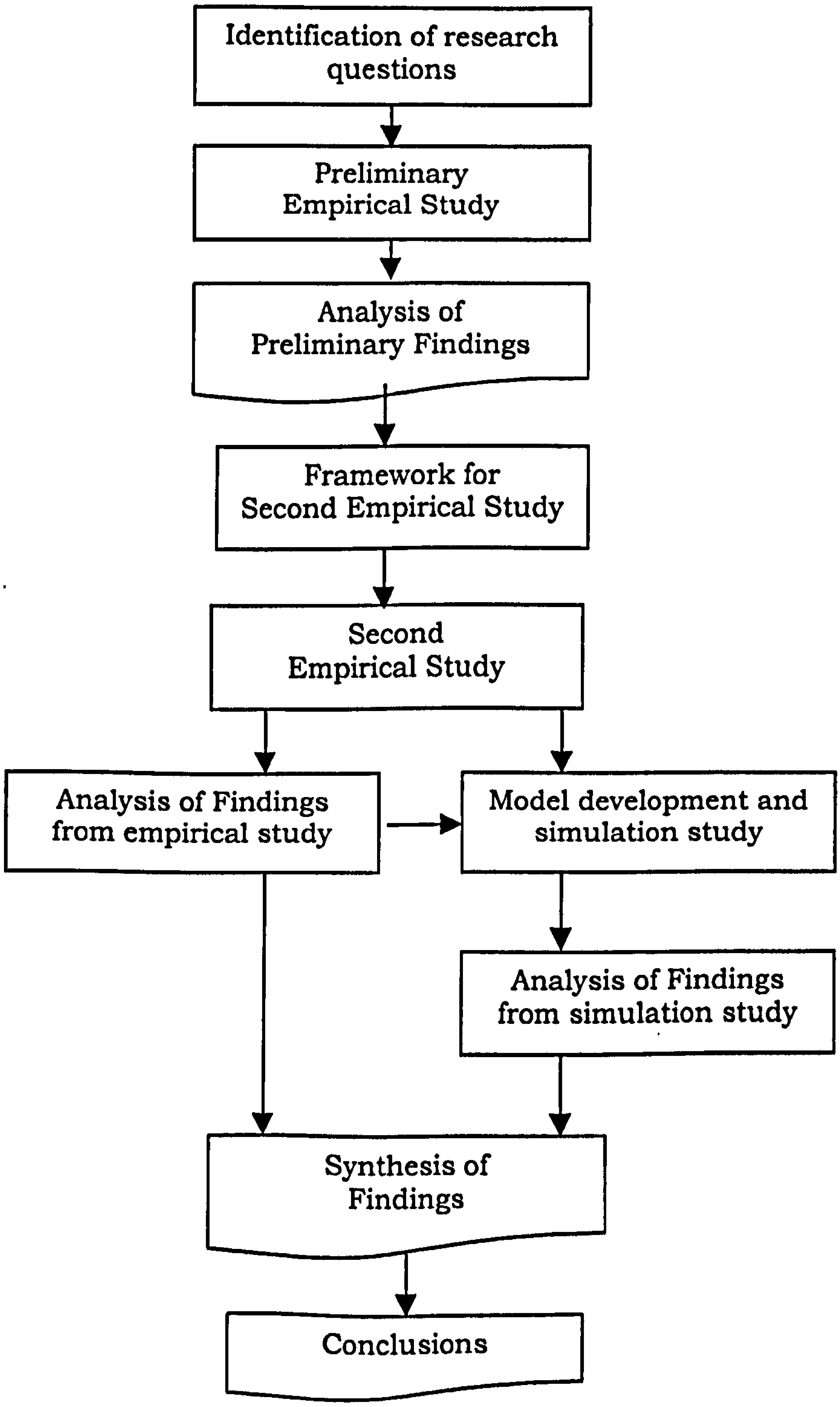


Figure 3.1 General overview of research stages

3.2 Formulation of research questions

Insights from the literature suggest that the main foundation in managing an international network of factories is to understand the configuration and co-ordination of the supply networks. The existing international operations literature focused on addressing the configuration and co-ordination of MNC supply networks. In reality, other types of ownership and relationships exist in international supply networks, which may affect their configuration and co-ordination. Thus, the first research question to be addressed in this study is:

Q1: Do international supply networks with different types of ownership show similarities or differences in the aspects of configuration and co-ordination?

The review of the existing literature also shows that there is very little work that explores the issue of product variety facing companies belonging to real international supply networks. Owing to this fact, the study also aims to answer the following questions:

Q2a: What are the variety-related issues facing the international supply networks across different industry sectors?

Q2b: How are different functions in the supply chain affected by product variety?

The review of the literature in supply chain management highlights the importance of recognising a company's demand pattern in order to devise the right supply chain strategy. Furthermore, several previous studies noted that high product variety potentially leads to demand uncertainty. This leads to the following research question:

Q3: Do real international supply networks across various industry sectors face different levels of demand uncertainty?

Supply uncertainty is another important issue commonly noted in the supply chain management literature. Supply uncertainty may be caused by the characteristics i.e. maturity and location of the supply base. The empirical study aims to address these issues by asking the following questions:

***Q4a**: Where do the real international supply networks buy their key materials?*

***Q4b**: What is the characteristic of the supply base?*

***Q4c**: Do real international supply networks across various industry sectors face different levels of supply uncertainty?*

Another important gap identified in the existing literature is the fact that there is almost no work that relates the issue of product variety with other factors in managing international supply chains particularly in relation to supply and demand uncertainty. In reality, more and more firms today produce a high level of product variety, which introduces more uncertainty in demand. On the other hand, given the international coverage of the supply network, many companies source materials globally leading to long and uncertain lead-times, hence the source of supply uncertainty. Current literature has not adequately explored the effect of demand and supply uncertainty in managing product variety within the context of international supply networks. Therefore, further understanding on how these factors interact and affect the performance of international supply chains is necessary. In particular, quantifying the above relationships would be useful. This study also aims to answer the following questions:

Q5: *What are the impacts of increasing product variety and supplier delivery uncertainty under a constant demand situation on supply chain performance?*

Q6a: *What are the impacts of increasing product variety and aggregate-level demand uncertainty when supplier delivery time is constant on supply chain performance?*

Q6b: *What are the impacts of increasing product variety and product-level demand uncertainty when supplier delivery time is constant on supply chain performance?*

Q6c: *What are the impacts of increasing product variety and both aggregate-level and product-level demand uncertainty when supply delivery time is constant on supply chain performance?*

Q7: *What are the impacts of increasing product variety when both demand and supply are uncertain on supply chain performance?*

The above research questions range from qualitative and less structured problems to well-structured problems with more or less quantifiable measures. Questions 1 – 4 are broad questions intended to provide general insights and qualitative interrelationships between various aspects in managing product variety within the context of international supply chains. These questions are addressed by conducting an empirical study involving real international supply networks due to the exploratory and qualitative nature of the problems. On the other hand, questions 5 – 7 specifically aim to demonstrate the interactions across the factors and quantify the potential impacts of the factors on the performance of international supply networks. In order to answer these questions, a simulation study is conducted. Further justification on the use of a simulation study is presented in section 3.4.

3.3 Empirical study

Several authors have suggested that empirical study, particularly through case studies, provides an appropriate method to address new topic areas in operations management for the purpose of theory building (Eisenhardt, 1989; Flynn et al., 1990; Voss et al., 2002). According to Eisenhardt (1989), the stages in building theory from case study research are: a) getting started, b) selecting cases, c) crafting instruments and protocols, d) entering the field, e) analysing data, f) shaping hypotheses, g) enfolding literature, and h) reaching closure. Similar stages as Eisenhardt's framework are applied in this study, which consists of the following five steps:

1. Identification of research questions
2. Case selection
3. Developing instruments for data collection
4. Data collection
5. Analysis

The research questions to be addressed in the empirical study have been identified in the previous section. In addition to identification of research questions, Eishenhardt (1989) also highlights that a priori specification of constructs might help to shape the initial design of theory building research. In our empirical study, several important constructs including configuration, co-ordination, uncertainties, and product variety are identified by synthesising findings from various streams of literature (see section 2.6). These factors will be included in the interview protocols.

3.3.1 Case selection

Selection of the case is the next important aspect in conducting a case study, as it helps to determine the limits of which research findings may be generalised and serves as a control barrier to external variations of these findings (Eisenhardt, 1989; Da Silveira, 1998). Case study research may apply theoretical sampling, where cases are chosen to replicate or extend the emergent theory. In this study, the cases are particularly chosen to fill some of the gaps in the current literature with respect to location of case company, industrial sector, focal company and type of ownership.

3.3.1.1 Evidence from manufacturing companies in Indonesia

As discussed in section 2.7, the literature in international operations focuses on presenting evidence from developed countries and addressing the linkage between a Multinational Corporation and its subsidiaries. Prasad and Babbar (2000) argue that more empirical studies that span a wider range of countries, particularly in developing countries, are needed to develop theories of international operations management. According to Vos (1997), a number of Asian newly industrialising countries led by Taiwan, South Korea, Hong Kong, and Singapore, followed by Thailand, Malaysia and Indonesia have emerged as important exporters of manufactured products and China and India have become more integrated in the world economy.

Indonesia is the world's largest archipelago and with a population of approximately 238.5 million, it offers great market opportunities for international manufacturing firms (Walker, 1996). Other attractions for foreign companies to invest in Indonesia include: the vast natural resources and availability of relatively cheap labour as compared to other countries in the region. As a result, more and more Multinational Corporations producing various products such as automotive, electronics, apparel, footwear, etc. established their subsidiaries in Indonesia. However, evidence from manufacturing companies in Indonesia is still lacking in the operations management literature. Therefore, it is felt to be valuable to gather and present evidence from manufacturing companies in Indonesia.

3.3.1.2 Cross sectors

This study aims to present multiple cases from several companies involved in different industry sectors that produce different types of product, in contrast to a lot of work in the existing product variety literature that addresses the problem in the automotive industry.

3.3.1.3 Manufacturing unit as focal company

While significant parts of value chain activities are conducted by subsidiaries and the role of these subsidiaries has been increasingly recognised, there have not been many studies that address the operational, configuration and co-ordination issues from the perspective of the subsidiaries (Oliff et al., 1989). Therefore, in this study we include companies that are subsidiaries of MNC and use them as focal companies in analysing the configuration and co-ordination of the international supply networks.

3.3.1.4 *Type of ownership*

Another objective of the empirical study is to gather insight from real international supply chains with different types of ownership that represent different degrees of vertical integration. The decision of owning a foreign facility (vertically integrated), either in the form of a wholly owned subsidiary or as a joint venture, as opposed to using a trading partner to conduct some or all parts of value chain activities (vertically disintegrated) potentially affects the operation of the network of factories. Therefore, these two types of ownership are the focus in this study.

To summarise, the empirical study presents evidence from companies in Indonesia that are involved in international supply networks through different types of ownership and that produce different types of products (Table 3.1).

Table 3.1 Summary of case studies

Number of cases	Focal company	Location	Type of ownership
6	Manufacturing unit	Indonesia	Subsidiary of Multinational Corporations
5	Manufacturing unit	Indonesia	Contract manufacturer
1	Management centre	UK	Multinational Corporation

Eleven companies are involved in the empirical study. Six out of eleven case companies in Indonesia are subsidiaries of Multinational Corporations. Five companies in Indonesia are contract manufacturers for foreign buyers. In addition to the cases from companies in Indonesia, an investigation is conducted in INTIMATE_WEAR, a company based in the UK that produces ladies underwear. INTIMATE_WEAR has several manufacturing facilities as well as using foreign contract manufacturers to conduct some of their operations.

3.3.2 Developing instruments for data collection

The study investigates several issues that have not been widely addressed in the literature. As a result, the empirical study is designed to be exploratory in nature. Multiple data collection methods are used in each case study including interviews, plant visits (observations) and company archives. A semi-structured questionnaire was developed in order to guide a face-to-face interview with representatives from each company.

3.3.3 Data collection

The data collection was divided into two stages. The first stage was conducted in July-August 2001 involving five companies. The first stage of the empirical study was mainly used as a 'pilot' study to gain preliminary insights on the problem domain. Interviews were conducted with representatives from different functions in the company including supply chain, production, planning, purchasing, or logistics. The interview lasts for 1 to 2 hours. The main constructs and questions used in the preliminary empirical study interviews are summarised in table 3.2.

Results from the preliminary empirical study were used to assess the validity of the empirical protocols and develop more comprehensive protocols for the second empirical study.

The second stage was conducted in June – July 2002. In the second stage of the empirical study, more detailed information regarding product variety and other challenges facing the case companies with respect to supply and demand uncertainty were collected. To obtain such information, the five case companies involved in the first stage of the empirical study were visited again. In addition, seven more companies were included. More intensive interviews were conducted in these seven companies using a more comprehensive list of questions. The questions asked in the second empirical study can be found in **appendix 1.**

Table 3.2 Semi-structured questions for preliminary empirical study

Constructs	Questions
Product and process characteristics	• Is the product for individual or industrial customers? • Does the product have a specific selling season? • How often is a new product introduced? • What are the characteristics of the manufacturing process?
Configuration of the supply network	• What are the key elements in the company's international supply network? • Where is each element located? • What are the responsibilities of each element? • What is the company's status of ownership?
Co-ordination of the supply network	• What mechanisms are used to co-ordinate activities conducted by different elements of the international supply networks? • What activities need to be co-ordinated? • Are the activities co-ordinated locally, regionally or globally? • What is the information shared between different elements in the international supply network?
Product variety	• What are the main product variants produced by the company? • What are the attributes that differentiate different product variants? • How does product variety affect the operation of international supply networks?
Challenges	• What are the challenges facing the international supply network

3.4 Simulation Study

3.4.1 Justification for the use of a simulation study

A supply chain is normally a very complex system with many interrelated elements. Obtaining firm understanding on the behaviour of a supply chain requires comprehensive observations, which necessitate the use of various methodologies. Each research methodology has its strengths and weaknesses and should then be applied selectively according to the type of research questions to be addressed. It has been discussed earlier that empirical study only provides general and qualitative insights of the behaviour of the supply chain. A simulation study has subsequently been chosen to complement the empirical study in order to gain deeper understanding on supply chain performance in managing product variety in the context of international supply chains. Wyland et al. (2000) argue that simulation has gained increasing popularity as a tool in supply chain management due to its strength in evaluating system variation and interdependencies. This enables a decision maker to assess changes in part of the supply chain and visualise the impact of those changes on the other parts of the system and ultimately on the performance of the entire supply chain. As simulation has proved to be a useful tool in the area of supply chain management, Ramdas (2003) suggests that it might be applicable in the context of variety management.

There are a number of considerations that influence the preference to use simulation over analytical or optimisation models in evaluating supply chain systems. First is the complexity of the system, which is determined by the number of elements involved in the supply chain system and the nature of their relationships and interactions. Analytical models typically can only be developed and work well when the complexity of a system is low. As Law and Kelton (2000) suggest, an analytical solution may be possible if a model is simple enough. When a system is highly complex, a valid mathematical model of such system is in itself complex, prohibiting any possibility of an analytical solution. They argue that in such a case 'the model must be studied by means of simulation, i.e., numerically exercising the model for the inputs in question to see how they affect the output measures of performance'. The second factor is the level of uncertainty or variability embedded within a system. Analytical models are typically too difficult to develop and/or to evaluate when a system has many variables with uncertain values. In supply chains, uncertainty or variability could be associated with demand, delivery lead time, quality of incoming materials, manufacturing processing times, and transit time (Lee and Billington, 1992; Davis, 1993). For supply chain systems with uncertainty, simulation is again a preferred tool of analysis as it can capture the dynamics of the uncertain system more effectively than the analytical models.

The above arguments provide a sound rationale to justify the use of simulation model in this study. We deal with product variety, which by itself is already a complex issue. Compounded with the international nature of the supply chains, where the issues of configuration, co-ordination, and uncertainties in supply and demand play significant roles, the whole system becomes even more complex, which suggests that the use of any analytical modelling would be prohibitive.

3.4.2 Nature of the simulation study

A simulation study may be aimed at evaluating system performance under various possible values of the relevant parameters (Byrne, 1992) or to obtain the best policy to be applied in a system under study. The system under study could be a real or a hypothetical system. Kritchanchai & MacCarthy (2002) differentiate simulation studies as:

1. A simulation study that replicates a specific existing system in order to explore the impact of new policies or other system changes. Levy (1995) is an example of a simulation study that falls into this category. As described in section 2.4, Levy developed a simulation model based on the international value chain of a personal computer manufacturer (CCT). Supplied by real data from the company, the simulation model is used to investigate the impact of disruptions on supply chain performance.
2. A qualitative simulation study that uses an assumed and hypothesised model to explore, understand and compare the behaviour of generic system types. Some studies that use this type of approach are Byrne (1992), Bonney et al. (1999) and Lummus (1995). Byrne (1992) uses a simulation model of a manufacturing system to evaluate the overall performance of the system under certain conditions and propose an approach to achieving lead-time reductions. Bonney et al. (1999) examine the effect of push and pull information flow on system performance using an assumed production system. Lummus (1995) developed a simulation model of a JIT production line in order to investigate the effects of sequencing production under various product mix combinations and various set up or processing time additions.

Different characteristics of these two types of simulation study are summarised in table 3.3.

Table 3.3 Characteristics of different types of simulation study
(Adapted from Kritchanchai and MacCarthy, 2002)

	Quantitative Simulation Study	**Qualitative Simulation Study**
Objectives of the study	Explore the impact of new policies or changes to existing system	Explore, understand and compare behaviour of generic system
Characteristics of system modelled	Specific, exists in some form thus enabling development of a model of the real system	Generic thus the simulation model has to be assumed or hypothesised
Reference state	Representing the system's current operating conditions	Reference set of input data needs to be established for the reference stage of experiments
Types of experimentation and analysis	Typically apply formal design of experiment and statistical analysis	Comparing the results to the reference state

Although the simulation model presented here is based on information from real cases, the model strives to capture generic characteristics of MNC supply networks and does not try to mimic any specific real system. The objective of the simulation study is to give insights on the potential impact of different factors on the performance of international supply networks. Therefore, no quantitative real data from the company is used in the simulation, as it would not be consistent with the objective of the study here.

Based on the above reasons, the simulation study presented here can be classified as **qualitative generic simulation study**. As shown in table 3.3, in this type of simulation study, a reference set of input data is normally established to develop a reference state against which the results of the experiments can be benchmarked.

A number of aspects need to be considered in order to determine the best simulation model approach to use. As can be seen from table 3.4, Law and Kelton (2000) classify simulation models based on three aspects including time handling (whether it is static or dynamic), the uncertainty to be accounted for (whether it is deterministic or stochastic), and state change (whether it is a discrete or continuous).

Table 3.4 Classification of simulation models
(Adapted from Law & Kelton, 2000)

Characteristics	Type of Simulation Approaches	
Time	**Static**	**Dynamic**
	A representation of a system at a particular time	A representation of a system as it evolves over time
Deterministic Vs. Stochastic	**Deterministic**	**Stochastic**
	A system that does not contain any probabilistic components	A model that contains at least some random input components
Discrete Vs. Continuous Change	**Discrete**	**Continuous**
	The value of variables change instantaneously at separated points in time	The value of variables change continuously with respect to time

Based on the above framework, our model can be classified as **dynamic, stochastic, and discrete**. This is believed to be appropriate for the following reasons. Firstly, in this study we develop a dynamic model, as the system we deal with is not static, but rather a system that evolves over time. For example, the inventory levels, the actual lead-time and the actual demand all change with time.

Secondly, the study deals with a stochastic system in the sense that it accounts for uncertainty in the two main factors, i.e. uncertainty in demand and in supply lead-time. The simulation model used here can therefore be classified as stochastic simulation model. Both the quantity of demand in a certain period and the length of the supply lead-time may be generated from a random number to represent uncertainty on these two factors, although in some set of experiments either or both of them have been assigned deterministic values.

Further consideration is required in deciding to develop discrete event as opposed to continuous simulation. According to Law & Kelton (2000), continuous simulation relates to the modelling over time of a system by a representation in which the state variables change continuously with respect to time. Typically, it involves differential equations that give relationships for the rates of change of the state variables with time. One of the main tools in continuous simulation is *industrial dynamics,* often called *System dynamics* (Pidd, 1998). System dynamics concentrates on three aspects of system structure (Forrester, 1961): 1) delays, 2) levels and 3) rates. Delays occur as material and information are rarely transmitted and received instantaneously. Level, sometimes also referred to as stock, represents a system state variable such as an inventory or a buffer. Rate or flow represents activity that continues dynamically in the system such as a production rate or a shipment rate. System dynamics method views feedback systems as interconnected sequences of levels and flow rates (Pidd, 1998).

On the other hand, according to Law & Kelton (2000), "discrete event simulation concerns the modelling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time". Some terminologies typically used in discrete event simulation are entities, events and activities. Entities are individual elements of the system that are being simulated and whose behaviour is being tracked. An event is an instant of time at which a significant state change occurs in the system. Operations and procedures, which are initiated at each event, are known as activities. Pidd (1998) argues that many applications of discrete event simulation involve certain kinds of queuing systems.

System dynamics has been used in the area of supply chain management. Towill (1996) states that by using system dynamics in supply chain redesign, he is able to generate added insight into a system's dynamic behaviour and particularly into underlying causal relationships. Ovalle & Marques (2003) develop system dynamics model to assess the impact of using e-collaboration tools on the supply chain performance. Spengler and Schroter (2003) use system dynamics to model an integrated production and recovery system for supplying spare parts. Using the system dynamics model allows firms to examine alternative strategies and policies. Having reviewed the applications of system dynamics in supply chain management it is found that:

- The major concerns are often with *stability* i.e. how does a system respond to changes in its inputs?
- It is mainly interested in consequence of events (causal loop or feedback)
- Key variables can be expressed in rates of change of variable within time

Pidd (1998) argues that despite the long history of system dynamics, there is scepticism among many management scientists of its value. He elicits two possible reasons for this, including:

- Its mechanistic approach may be a limiting factor to practising manager.
- System dynamics is arguably not a highly refined and accurate tool. As system dynamics aims to explore the dynamics of feedback systems in terms of their stability and responses to external shock, the presenting stability may be too gross.

On the other hand, there is also a large number of examples on the use of discrete simulation for supply chain management. Persson and Olhager (2002) demonstrate the value of discrete event simulation modelling in evaluating alternative supply chain designs that differ in terms of the level of integration and synchronisation on key performance measures including quality, lead-time and costs. Al-Zubaidi and Tyler (2004) develop a discrete simulation model to investigate the effects of improved retailing and supply procedures on financial and other performance measures using two supply strategies i.e. fixed quantity re-ordering and fixed interval re-ordering. Tiger and Simpson (2003) develop discrete-event simulation to assist a Multinational Company in understanding the impact of material flow from the US to the Asia Pacific region and to allow flexibility in the supply chain.

Having reviewed the applications of discrete event simulation in the context of supply chain management, it is clear that it takes a microscopic approach by concentrating on the *state changes* and *interactions of individual entities*. In contrast, system dynamics operates at a much more *aggregate level* by concentrating on *the rates of change* of populations of entities (Pidd, 1998). Furthermore, system dynamics does not highlight the interaction of entities at discrete points of time. Thus, it is difficult to trace back which events cause the behaviour. It is also very hard to incorporate complex logic into a system dynamics model, while discrete event modelling is very flexible.

Having appreciated the different approach of system dynamics and discrete event simulation, the choice is made based on the fitness of the approach to the objective and emphasis of the study. The following rationale is used in selecting the simulation approach:

- Our study is mainly aimed to demonstrate the impact of factors on performance. We are not interested in exploring further the response of the system to the treatment (factor changes) i.e. the inter-relationships do not need to be described in a feedback loop.
- We want to be able to understand the impact of a certain factor on the supply chain performance, thus it is important to be able to trace back which events cause the resulting effect.
- Our model contains complex logic to represent demand and supply uncertainty and product variety.
- Variables used in the study can be satisfactorily described in discrete changes. For example, variety can be increased from one to five, the level of inventory changes when a delivery from a supplier arrives and/or when a certain amount of materials is taken to satisfy a production schedule rather than changing continuously with a certain rate.

Based on the above considerations, the use of **discrete event simulation** is felt to be more appropriate for this study. By using discrete event simulation the values of main variables observed in this study only change when an event occurs, so it makes it clear when significant events have occurred in the simulation. This also means that the changes in the key performance metrics can be traced back to a certain factor.

3.5 Concluding Remarks

This chapter has presented and justified the methodology used in conducting the research, which include both empirical and simulation studies. In the following chapter, results from the empirical study are discussed and analysed. Chapter 5 explains the process to incorporate the information obtained from the empirical study to develop a simulation model. Results from the simulation experiments are discussed in chapters 6 – 8.

Chapter 4
Empirical Study

4.1 Introduction

This chapter describes the findings from the empirical study. Each case company is given a name that reflects its unique characteristic, in order to easily identify each case in the analysis. The name given to each case is summarised in table 4.1.

Table 4.1 Name for each case

Case description	Name
Shoes manufacturer	SHOES
Light bulb manufacturer headquartered in Asia	ASIA_BULB
Light bulb manufacturer headquartered in Europe	EURO_BULB
Consumer food manufacturer	FOOD
Heat exchanger manufacturer	HEATEX
Chemical (silica) manufacturer	SILICA
High fashion ladies wear manufacturer	FASHION_WEAR
Casual garment manufacturer with two selling seasons	CASUAL_TWO
Casual garment manufacturer with continuous selling season	CASUAL_CON
Fish processor	FISH
Furniture manufacturer	FURNITURE
Intimate wear manufacturer	INTIMATE_WEAR

This chapter is organised as follow. Descriptions of twelve case companies involved in the empirical study are provided in the following section. Analyses of the empirical findings are presented in section 4.3. First, the configuration and co-ordination of the case companies are analysed in sections 4.3.1 – 4.3.2. In section 4.3.3 the supply networks belonging to Multinational Corporation (MNC) are classified based on the configuration and co-ordination strategies. Comparisons between supply networks belonging to MNC and contract manufacturers are provided in section 4.3.4. This is followed by analysis on configuration and co-ordination of INTIMATE_WEAR, a company that divides production between their own manufacturing units and contract manufacturers (section 4.3.5). The implications of configuration and co-ordination strategies on the international supply networks operations is summarised in section 4.3.6. In section 4.3.7 – 4.3.9 the issues faced by each case company in terms of product variety, demand uncertainty and supply uncertainty are analysed. The overall challenge facing the real international supply networks is reviewed in section 4.3.10. Finally, a summary of findings from this chapter is provided in the final section.

4.2 Description of case companies

4.2.1 Shoe manufacturer - SHOES

- *Product and supply network characteristics*

SHOES is one of the *production units* of an international group producing high quality leather shoes headquartered in Europe. The group produces various types of shoes including casual, outdoor, men, ladies, kids and semi-sports shoes for two selling seasons i.e. spring-summer and autumn-winter. In addition to SHOES, the international group has four other *production units* located in Denmark, Portugal, Slovakia and Thailand. The production unit in Indonesia specializes in producing shoe uppers for the group, whilst the finishing processes i.e. adding shoe uppers with soles to make finished shoes are held in other facilities of the group. The production unit in Indonesia satisfies approximately 40% to 50% of total shoe upper demand in the group.

- *Value chain activities*

Design and product development processes are conducted by headquarters but with a strong involvement from the subsidiary in Indonesia in order to transform the design into good and comfortable shoe uppers. Before starting actual production for the next season, the subsidiary in Indonesia is required to make samples of production. The marketing team at headquarters will screen the samples to decide (forecast) the volume and style of production. Based on the sales forecast, headquarters will allocate production orders among its network of subsidiaries. The production of shoe uppers itself typically involves significant manual work. When the shoe uppers are completed, they are shipped by sea to another group's facilities for subsequent processing according to the allocation set by headquarters. Finished shoes are distributed via the group's *Distribution Centre* and *Sales Agents*.

- *Materials and supply base*

The main materials required in the production of shoes are rawhides, which are processed into semi-finished and finished leather. Other materials required for production including reinforcement, yarn and accessories. A great amount of the materials (70-80%) are obtained from suppliers in Europe. Procurement of raw material from these suppliers takes approximately 8 weeks from placement of order until materials are ready to be shipped and 5 weeks for sea shipment.

4.2.2 Asia light bulb manufacturer – ASIA_BULB

- *Product and supply network characteristics*

ASIA_BULB is a *wholly owned subsidiary* of a Japanese Multinational Company producing various electrical products ranging from consumer, industrial to component products. The subsidiary in Indonesia is one among three companies in the group that produce light bulbs, while the two other subsidiaries are located in Japan and China. Each of these subsidiaries produces different types of light bulbs. ASIA_BULB products are mainly sold to worldwide markets and only 10% are sold locally (Indonesia market). The light bulb produces by ASIA_BULB proliferates into a great number of product variants due to different colour and shade of the bulb, and electrical specifications (voltage and wattage) required by different countries.

- *Value chain activities*

Product development activities are conducted by the headquarters in Japan. ASIA_BULB has a *National Sales Agent* that is responsible for sales and marketing activities under the control of a *Regional Sales Office* in Singapore. Sales agents and regional offices send sales forecast for their respective regions to the headquarters in Japan. The headquarters will determine the aggregate production requirement and send four months rolling production requirement to ASIA_BULB. Production of the light bulbs requires some machining operations (such as the glass furnace, bulb blowing, capsule production) with high-tech equipment as well as manual work (assembly). Finished products are packed according to each market destination and their distribution is handled by the group's sales office in Singapore.

- *Materials and supply base*

In addition to the glass globe, production of light bulbs requires other components such as semiconductors. A great amount of the materials required for production is imported from suppliers worldwide (Holland, Poland, Japan, etc.), which on average require three months to procure.

4.2.3 Europe light bulb manufacturer – EURO_BULB

- *Product and supply network characteristics*

EURO_BULB is the second light bulb manufacturer involved in this study. EURO_BULB is part of a Multinational Corporation headquartered in Europe. The MNC has a lot of subsidiaries all over the world, which are divided into several regions. EURO_BULB is one of the subsidiaries operating in the Asia Pacific Region. The group has two other manufacturing units within this region located in Thailand and China. Each manufacturing unit, called *supply centre*, typically has core products that they produce for the region. However, some product variants are made in every supply centre. Light bulbs produced by EURO_BULB are mainly differentiated by shape of the bulbs and electrical specifications.

- *Value chain activities*

Similar to the previous cases, product design and development activities in EURO_BULB network are mainly handled by its corporate headquarters. However, each *supply centre* has the authority to develop the products according to local or regional needs. The group has a *Commercial Organisation* that is responsible for sales and marketing activities in each country. The commercial organisation provides demand information to the *Regional Office* in Hong Kong. The regional office then allocates production of demand across supply centres to ensure balance load between supply centres in the region. It has the authority to re-route capacity when there is overload in one of the supply centres to another supply centre that has spare capacity.

- *Materials and supply base*

Similar to ASIA_BULB, production of light bulbs requires glass for the globe, components and semiconductors. A small proportion of components used in production are bought from a *sister company* located close to EURO_BULB's factory. However, the majority of the components have to be brought from European suppliers. Lead times to procure imported materials range from 6 weeks to 12 weeks. This comprises of factory lead-time, transportation via sea and clearance time.

4.2.4 Consumer Foods Manufacturer - FOOD

- *Product and supply network characteristics*

FOOD is a wholly owned subsidiary of a European Multinational Company producing various food products ranging from beverages, confectioneries, to instant milks. The group's supply network is scattered worldwide with the establishment of their subsidiaries in almost every country in the world. In South East Asia and Pacific region, the group has subsidiaries in Malaysia, Philippines, Thailand and Australia. Each subsidiary has its core product(s) or brands to produce. FOOD is the main producer of condensed milk in Asia Pacific Region. For this type of product, FOOD not only satisfies the Indonesian market but also other countries in South East Asia.

- *Value chain activities*

Research and development activities are held in the *Corporate Innovation Centre* located in the corporate headquarters. This centre provides a basic formula that each subsidiary may customise according to local market preferences. In order to manage demand for their core products as well as other products produced in a sister company, each subsidiary has several *supply planners* working in a *national office* in each country. Each supply planner manages demand of several products or brands. Supply planners handling FOOD's core products will receive sales forecasts from local distributors and demand requirement from supply planners in importing countries. Supply planners determine a weekly production plan and send it to FOOD to be executed. The national office also has supply planners in charge of importing the group's products produced by other subsidiaries in different countries.

- *Materials and supply base*

The main materials required for FOOD production is skimmed milk and sugar. Procurement activity for skimmed milk is conducted through corporate headquarters in order to gain economies of scale and quantity discount. This forces FOOD to place their orders for skimmed milk up to three months in advance to allow for transportation, which on average takes one month for sea shipment from Europe.

4.2.5 Heat Exchanger Manufacturer – HEATEX

- *Product and supply network characteristics*

HEATEX is a joint venture between a European group and an Indonesian entrepreneur. HEATEX develops and manufactures heat exchanger units and heat exchanger systems. The group has other subsidiaries located in Germany, Hungary, Russia and Switzerland.

- *Value chain activities*

The corporate headquarters in Europe conducts product design and development activities. Tactical and strategic issues, such as investment decisions made by the subsidiary in Indonesia, have to be consulted with corporate headquarters. Other than this, the subsidiary in Indonesia performs most of their day-to-day activities without a lot of involvement from headquarters.

HEATEX manufactures heat exchangers based on customer orders. Customers mainly come from neighbouring countries such as Thailand, Malaysia and Singapore. They are usually contractors in charge of developing or installing cooling systems in food manufacturing, office or public facilities. The company only produces some parts of the entire cooling system. Sometimes the customer comes with specific needs, so the company has to customise its standard products according to the customer order. In this business, the company not only sells products but also services to satisfy the customer. Therefore, the company also offers assistance in finding tailor-made solutions for the customers and offers 18 months customer service guarantee.

- *Materials and supply base*

Production of heat exchangers requires various components including fan, motor, plates, pipes etc. The components are mainly procured from suppliers in Europe. To ensure standard quality of materials as well as achieving economies of scale, the procurement of material is managed by headquarters. Procurement of materials typically takes two months.

4.2.6 Chemicals Manufacturer - SILICA

- *Product and supply network characteristics*

SILICA is a wholly owned subsidiary of a multinational group that produces different types of chemicals. The group has three operational sites producing silica located in Europe, Brazil and Indonesia. The manufacturing site located in Europe also acts as the corporate headquarters and R&D centre. Production in this site is targeted to serve the European, Middle Eastern and African markets. The production site in Brazil aims to serve the North and South American markets. For the Asia Pacific region, the group has *regional offices* located in Singapore, *sales offices* in Tokyo, Melbourne, Hong Kong, Shanghai and Jakarta, and a *production site* in East Java, Indonesia. The production site in Indonesia produces two main products: *abrasive components (AC)* and *thickener components (TC)* used in toothpaste manufacture. The company's products are sold to local customers (50%) as well as to other Asia Pacific countries. A majority of local demand comes from UI, a Multinational Company producing personal care products that is located close to the SILICA's factory. Foreign customers come from Vietnam, The Philippines, Thailand, and New Zealand and occasionally also come from the Middle East and South Africa.

- *Value chain activities*

Product development activities are concentrated in R & D centres in the UK, with a lot of inputs from regional offices. In addition, corporate headquarters are only involved in strategic and long-term decisions, with very limited control on day-to-day operations of SILICA. The regional office in Singapore is in charge of co-ordination of sales and development of the group's business in the region. The sales offices spread in four countries in Asia Pacific become the focal points for the group to understand their customer-specific needs - which may vary across the countries - and offer a better solution for them. In managing their day-to-day operations, SILICA and UI, as their major customer, established a long-term contract, where UI provides SILICA with a yearly forecast of their material requirements. This is considered by SILICA as a yearly production plan that is broken down into monthly plans. On a weekly basis the customer will send a confirmation order.

- *Materials and supply base*

The main materials used by SILICA are glass - which is mainly imported from Malaysia and Europe. In addition, the production also requires additional chemicals that they procure from suppliers in Indonesia and Australia.

4.2.7 High Fashion Ladies Wear Manufacturer – FASHION_WEAR

- *Product and supply network characteristics*

The first contract manufacturer involved in this study is FASHION_WEAR, a privately owned garment manufacturer. FASHION_WEAR produces various styles of ladies wear from fairly plain casual wear to high fashion dresses accessorised with embroidery and sequins. Their buyers range from independent shops or wholesalers in Germany, Japan or USA to agents for fashion houses such as Gucci or La Ricci.

- *Value chain activities*

FASHION_WEAR starts its operations every year by generating ideas and making samples of products for the next summer season. In some cases the buyers come with their own design/idea of products. However, in most cases FASHION_WEAR prepares samples of products for wholesalers or agents. The wholesaler screens the samples and organises an exhibition where potential customers (agents for boutiques, shops or fashion houses) can see the company's latest creation. Following the sample and exhibition period customers typically place firm orders, which then trigger the production process. The production stages, which include cutting, sewing, putting on accessories and finishing, are labour intensive. In each stage of production a quality check is conducted. However, the buyers usually conduct another quality check. Finished garments (unlabelled) from FASHION_WEAR are shipped by wholesaler's logistics company and after putting on their own labels, wholesalers sell them to end customers via shops and boutiques. Although FASHION_WEAR has worked with some of their customers for a long period of time, they do not have a formal long-term contract with any of their customers. Due to the seasonal nature of the market for its products, the company faces periodic swings in their demand.

- *Materials and supply base*

The company's principal material is cloth or fabrics, which they buy in the *grey* state (undyed) from their suppliers in China.

4.2.8 Casual Garment Manufacturer with two seasons – CASUAL_TWO

- *Product and supply network characteristics*

CASUAL_TWO is a privately owned Indonesian company that manufactures and exports apparel products. CASUAL_TWO produces dresses, blouses, skirts, trousers, jackets and shirts. The company makes use of 95% of its capacity to produce products for foreign customers while only 5% of the capacity is used to produce products for the local market. Like most garment manufacturers in Indonesia, CASUAL_TWO mainly works as contract manufacturer for foreign wholesalers, retailers or through trading agencies. CASUAL_TWO's main customers come from Western Europe (Germany, United Kingdom, Netherlands, and Norway), United States, Canada and Japan.

- *Value chain activities*

CASUAL_TWO operations follow their foreign customers, which work in two production cycles: the winter season and the summer season. Prior to the start of each season, the wholesaler or trading agency typically come with their own idea of products and request the company to develop a sample. At the same time, the company also prepares samples of materials (fabrics) and accessories to be shown to their customer. Once the customers place a formal order, CASUAL_TWO starts producing the products without much involvement from the customers. CASUAL_TWO does not formally have a long-term contract with any of their customers. However, they do have customer(s) that continuously buy from them for years. Similar to FASHION_WEAR, CASUAL_TWO also faces periodical swings in their demand.

- *Materials and supply base*

Materials used in the production are fabrics (jersey and lycra) and accessories. The majority of these materials are obtained from local suppliers. Procurement of materials typically requires 4 – 6 weeks.

4.2.9 Casual garment manufacturer with no specific selling season – CASUAL_CON

- *Product and supply network characteristics*

CASUAL_CON is a family-owned company that produces various garment products such as blouses, trousers, tops, T-shirts etc. A small proportion of their capacity is also used to produce peripheral products such as pillowcases, napkins etc. The company is 100% export-oriented and their main markets include the UK, France and USA.

- *Value chain activities*

Unlike other garment manufacturers that usually produce in accordance with the selling seasons of their customers (winter and/or summer), CASUAL_CON production is not driven by specific selling seasons. They continuously produce various samples of products and send them to their potential customers (wholesaler or trading agency in the countries noted above) throughout the year. If the customers like the sample, both parties will negotiate on the price and due dates. Following these processes if the buyer and customer reach an agreement, the customer will place purchase orders. Throughout these processes the company and their potential customers are mediated by *agents*. These agents are the customers' representatives that are co-located with the contract manufacturer. The agents usually have more knowledge on the market preferences. The main role of an agent is to help CASUAL_CON in creating new ideas that match the fashion and preferences in the designated market. They also help in deciding the materials to be used for production and supervision of production. The agent is also actively involved in the quality control process. Finished products will not be shipped without approval from agents.

CASUAL_CON and its customer are directly in touch on the price negotiation and payment. CASUAL_CON has regular buyers that have continuously bought from them for more than 7 years. Despite the lengthy period of business relationship between buyer and CASUAL_CON, there is still no long-term contract between both parties.

- *Materials and supply base*

Materials used in production are cotton (jersey) and accessories such as sequins. CASUAL_CON mainly buys material from local supplier. Lead-time to procure material is approximately 7 – 10 days.

4.2.10 Fish Processor – FISH

- *Product and supply network characteristics*

The fourth contract manufacturer process fresh fish into 'semi finished' fish ready to be used as ingredients in various food products. The company's products are differentiated based on the processing required. The company's major customers include a fried rice manufacturer from Japan, and food manufacturers from Netherlands and USA. In addition, the company also actively seeks new customers from all over the world.

- *Value chain activities*

Unlike the garment manufacturers, FISH has no specific selling seasons. Throughout the year, customers may come and place orders. The customers specify what type of fish that they want (usually in term of sizes) and how they would like it to be processed. The processes may include grading (separating raw fishes into different sizes), removing heads from the fish, peeling the skins, cutting, dividing, cooking, etc. All these processes are conducted manually. Although FISH has loyal customers that continuously buy from them, there are no formal contracts between FISH and their customers. As a result, FISH has very little information regarding demand from the customers.

- *Materials and supply base*

The company buys fish as its main material for its production from farmers located in various places in Indonesia. Their business depends greatly on the supply of fresh fish, especially those that meet the required sizes and quality. This makes the procurement activities in this company quite complex and depends heavily on forecast and stocks of materials.

4.2.11 Furniture Manufacturer - FURNITURE

- *Product and supply network characteristics*

FURNITURE is a privately Indonesian owned company that produces various types of wooden-based furniture ranging from furniture's components - such as spindles and turnings - to finished furniture such as indoor and outdoor furniture, bedroom set etc. FURNITURE's customers mainly come from USA, UK, Japan and Australia.

- *Value chain activities*

The company produces the products based on customer orders. The customer may deal directly with the company. However, most of the times FURNITURE works with *a trading company*, which acts as an intermediary between the company and their customer. The customer or trading company usually comes with their general product specifications including the types of material (wood) to be used and the type of packaging. FURNITURE proposes a price and negotiates with the customer or trading company. Following this process, if both parties agree on the price, the company starts the sampling process. Based on the samples customers will place a purchase order. The production processes includes kiln-drying (to dry the wood), preparation of materials (cutting, dividing, moulding), processing, finishing and packaging. The customer or trading company usually places their representatives in the company to conduct quality control. Finished products cannot be shipped if they have not been approved by the customer or trading company's quality controller.

- *Materials and supply base*

FURNITURE mainly purchases materials (wood) from Indonesian suppliers. However, there are cases where customers or the trading company demand specific materials for their products, which have to be imported. The lead-time to procure imported materials is up to 2 months. For woods that are used regularly such as pine or timber the company usually keeps some materials in stock.

4.2.12 Intimate Wear Manufacturers – INTIMATE_WEAR

- *Product and supply network characteristics*

INTIMATE_WEAR is a wholly owned subsidiary of an American Multinational Corporation involved in various business sectors including foods and beverages, household and body care and apparel. INTIMATE_WEAR produces 'intimate' products, which include ladies underwear (bras and briefs) and nightwear. INTIMATE_WEAR's business is divided into two elements:

1. *Private brand sector*, which deals with the manufacturing of products for the customer bearing the customer's label.
2. *Branded label sector*, which deals with the manufacturing of products bearing the company's own label.

In this study, we focus on the operation of the INTIMATE_WEAR private brand sector.

- *Value chain activities*

Customers for INTIMATE_WEAR private brand sector are major retailers in the UK. INTIMATE_WEAR appoint an account manager for each customer. Each account manager has a merchandiser that works closely with the customer. Every year the account manager and customer determine the yearly sales anticipation and range of products to produce for certain selling seasons. The sales anticipation is translated to demand requirements. Production of demand requirement can be done in the company-owned facilities or bought from contract (offshore) manufacturers.

INTIMATE_WEAR manufactures some of its products in their own manufacturing units. They own manufacturing sites for cutting and sewing operations in Northern Ireland and Morocco. They also have manufacturing sites dedicated for sewing operations in Turkey and Tunisia. In addition to production in company-owned facilities, 20% of INTIMATE_WEAR products are sourced from offshore manufacturers in Indonesia, Turkey and Sri Lanka.

- *Materials and supply base*

Materials required for production conducted in INTIMATE_WEAR manufacturing units are bought from European countries such as Germany, Italy, Spain and the UK. On the other hand, the materials used in contract manufacturers' production are obtained from local supply base. Two of their contract manufacturers located in Turkey and Indonesia are vertically integrated companies that can produce main materials such as fabrics on-site.

4.3 Analysis of Findings

The empirical findings are analysed in several sections. The first analysis examines the configuration and co-ordination strategies applied by each case company. As suggested previously, case companies in Indonesia are either a subsidiary of MNC or contract manufacturer for foreign buyer. INTIMATE_WEAR's supply network is unique as it consists of company-owned facilities and contract manufacturer. The results from case companies in Indonesia provide the perspective of an element in international supply network. Therefore, their perspectives are focused on the configuration of partners and linkages that are directly related to their operation.

INTIMATE_WEAR provides broader perspective of the configuration and co-ordination of their supply network.

To accommodate the different perspectives, configuration and co-ordination of manufacturing companies in Indonesia and INTIMATE_WEAR case are analysed separately. Analyses provided in sections 4.3.1 – 4.3.4 examine findings from manufacturing companies in Indonesia. The focus is to compare the configuration and co-ordination characteristics of international supply network under common (MNC supply network) and different ownership (contract manufacturer). This is followed by section 4.3.5 that discusses the configuration and co-ordination of INTIMATE_WEAR case.

The following terminologies are used to refer to the cases during the analysis:

1. Companies in Indonesia that belong to a Multinational Corporation supply network are referred to as MNC supply network.
2. Companies in Indonesia that work as contract manufacturers for foreign buyer are referred to simply as contract manufacturers supply network
3. The network of subsidiaries and contract manufacturers belonging to INTIMATE_WEAR are referred to as INTIMATE_WEAR supply network.

4.3.1 Configuration of Manufacturing Companies in Indonesia

4.3.1.1 Product and industry characteristics

General information regarding the 11 manufacturing companies in Indonesia are summarised in table 4.2. In general, the contract manufacturers produce less sophisticated products with low technological content. The contract manufacturers are involved in apparel, food processing and furniture industries characterised by relatively 'mature' manufacturing processes and technologies. The rate of development in product and process technology in these industries is relatively slow. Furthermore, the production process mainly consists of manual work. In FISH case, the contract manufacturer conducts very basic processes such as peeling, cutting, or cooking raw fish, which are labour intensive tasks. In the apparel and furniture industry, although the customer preferences change rapidly from time to time, the basic process technology remains relatively the same. The six MNC supply networks are involved in the industries where a considerable amount of capital investment is required. FOOD and SILICA have high technology processing lines. In these two companies, only a small degree of the production process is conducted manually. Heat exchanger manufacturing also involves a high degree of machine work conducted by a skilled labour force. EURO_BULB, ASIA_BULB and SHOES have production processes that consist of machining processes and manual assembly work.

4.3.1.2 Elements involved in the supply networks

Fundamental differences are found with respect to elements involved in MNC supply networks and the elements of contract manufacturers supply network (Figure 4.1). MNC supply networks typically include suppliers, manufacturers, other subsidiaries, corporate headquarters and end customers. The two light bulb manufacturers sometimes bought their material from other subsidiaries belonging to the same parent companies. SHOES produces upper part of the shoes that have to be finished by other subsidiaries in the network.

Table 4.2 General characteristics of the case companies

Characteristics	SHOES	ASIA_BULB	EURO_BULB	FOOD	SILICA	HEATEX	FASHION_WEAR	CASUAL_TWO	CASUAL_CON	FISH	FURNITURE
Main product	Shoe uppers	Light bulbs	Light bulbs	Instant & Condensated milk	Abrasive & thickener chemicals	Heat Exchanger	High fashion ladies garment (Sequin)	Casual garment (jersey)	Casual garment	Semi processed shrimp	Component and Furniture
Consumer /Industrial	Consumer	Consumer	Consumer	Consumer	Industrial	Industrial	Consumer	Consumer	Consumer	Industrial	Consumer
International Engagement	Joint Venture With Multinational Company *(Headquarters in Denmark)*	Wholly Owned Subsidiary of Multinational Company *(Headquarters in Japan)*	Joint Venture with Multinational Company *(Headquarters in Holland)*	Wholly owned subsidiary of Multinational Company *(Headquarters in Switzerland)*	Wholly owned subsidiary of Multinational Company *(Headquarters in UK)*	Joint Venture with Multinational Company *(Headquarters in Germany)*	Contract manufacturer of foreign buyer	Contract manufacturer of foreign buyer	Contract manufacturer of foreign buyer	Contract manufacturer of foreign buyer	Contract manufacturer of foreign buyer
Market	Global	Global	Regional (Asia Pacific)	Regional (Asia Pacific)	Regional (Asia Pacific)	Regional (Asia Pacific)	Europe, Japan, USA	Europe, USA, Canada & Japan	UK, France, USA	Japan, Holland, USA	USA, UK, Japan and Australia
Supply base	- Europe - Own Tannery Facility	- Worldwide - Sister Company	- Worldwide - Sister Company	Worldwide	Malaysia & Europe	Europe	Local & foreign	Local	Local	Local	Local & foreign
Location of Other subsidiaries	Thailand, Slovakia, Portugal & Denmark	Japan & China	Thailand & China	Malaysia, Philippines, Thailand & Australia	United Kingdom & Brazil	Germany (2), Hungary, Russia, and Switzerland	-	-	-	-	-
Types of Process	Batch Manufacturing	Batch Manufacturing	Batch Manufacturing	Continuous Manufacturing	Continuous Manufacturing	Job Shops	Batch Manufacturing	Batch Manufacturing	Batch Manufacturing	Flow Shop	Job Shops – Batch Manufacturing

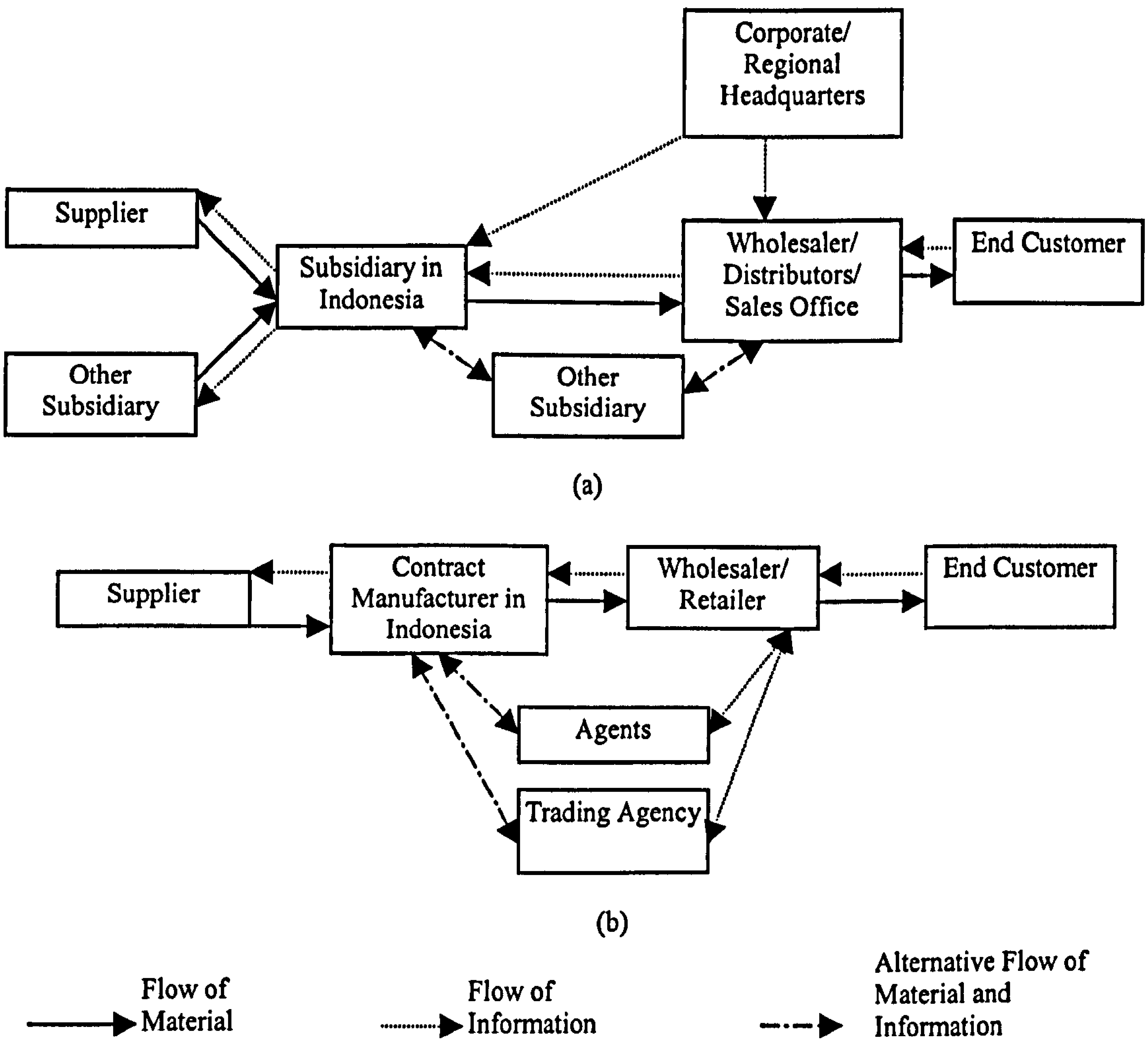


Figure 4.1 Typical elements involved in MNC supply network (a) and contract manufacturer supply network (b)

The contract manufacturer supply networks investigated in this study typically consist of suppliers, a contract manufacturer in Indonesia and foreign retailers or wholesalers as buyers. The three apparel contract manufacturers and the furniture manufacturer sometimes deal with agents or trading partners as intermediaries between them and the foreign buyer. The role of export intermediaries or traders in connecting manufacturers and foreign buyers has gained increasing attention in international business studies (Peng and Ilinitch, 1998).

4.3.1.3 Location of elements in the supply networks

Having identified key elements involved in both MNC and contract manufacturer supply network, the geographical span between elements in the supply network is investigated. While companies belonging to MNC supply networks generally buy their materials from foreign suppliers, the contract manufacturers appear to use local suppliers extensively. On the other hand, the six MNC subsidiaries in Indonesia satisfy regional and global markets while contract manufacturers mainly satisfy foreign markets.

4.3.1.4 Value chain configuration

The next analysis investigates which value activities are conducted by each of the elements in the supply network. Table 4.3 summarises the configuration of value chain activities in each supply networks. Unsurprisingly, all the companies are in charge of manufacturing activities. However, the results vary with respect to other activities. Two of the contract manufacturers i.e. FASHION_WEAR and to some extent CASUAL_CON, develop their own product designs in addition to producing designs brought by foreign buyers.

On the other hand, the six MNC subsidiaries depend on their respective corporate headquarters to conduct research and development activities. In all MNC supply networks, research and development activities are co-ordinated globally by corporate headquarters. None of the contract manufacturers sell directly to the end customer. Thus, they are not involved in sales and marketing to end customers.

Table 4.3 Configurations of value chain activities

Characteristics	SHOES	ASIA_BULB	EURO_BULB	FOOD	SILICA	HEATEX	FASHION_WEAR	CASUAL_TWO	CASUAL_CON	FISH	FURNITURE
Consumer /Industrial	Consumer	Consumer	Consumer	Consumer	Industrial	Industrial	Consumer	Consumer	Consumer	Industrial	Consumer
Product Development	NO	NO	NO	NO	NO	NO	YES	NO (customer)	YES (with help of agent)	NO (customer)	No (customer)
Demand Management	NO (Handled by Headquarters)	NO (Handled by Headquarters)	NO (Handled by Regional Office in Hong Kong)	NO (Handled by Planner in National Office in Jakarta)	YES (Co-ordination with Regional office in Singapore)	YES (Co-ordination with headquarters)	NO	NO	NO	NO	NO
Customer Service	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO	NO
Procurement	YES	YES	YES	NO	YES	NO	YES	YES	YES	YES	YES
Production	YES (Semi- finished)	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Quality Control	YES	YES	YES	YES	YES	YES	YES (Second quality check conducted by customers)	YES	YES (with high involvement of agents)	YES	YES (with great involvement from trading company's representative)
Distribution	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO	NO
Sales & Marketing	NO (Handled by Sales agents & Headquarters)	NO (Handled by Sales Agents in the group)	NO (Handled by Commercial Organisation in the group)	NO (Handled by National Office in Jakarta)	YES	YES	NO	NO	NO	NO	NO

Note: Yes refers to activities conducted by supply chain element i.e. focal company; No refers to activities conducted by other elements of the supply chain

The contract manufacturers begin their operations when they receive orders from a buyer. Once the products are finished, the distribution, sales and marketing of the products are handled by buyers.

In the MNC supply networks, distinct differences are found in terms of the element that conduct the customer-related activities (demand management, customer service, sales and marketing and distribution activities) and procurement activities. Two companies producing intermediary (industrial) products, i.e. HEATEX and SILICA, handle all the customer- related activities. On the other hand, the other four companies that produce customer products are not in charge of any of those activities. This finding supports a proposition by DuBois et al (1993). They suggest that companies producing intermediary (industrial) products where close contact with customers is necessary to accommodate their specific needs would put greater emphasis on market responsiveness. As a result, the subsidiary is given greater responsibility to deal directly with the customers.

Interesting evidence is found in terms of procurement activities. All the contract manufacturers conduct the procurement of materials required to production directly. Four of the case companies belonging to MNC supply network have the authority to procure the materials directly, except for HEATEX and FOOD. In these two companies, procurement of main materials is held centrally by their respective head offices. In the FOOD case, the procurement of skimmed milk is handled directly by its head office in Europe. Similarly, HEATEX's head office in Europe handles the procurement of major materials such as plates, motors or fans for heat exchanger manufacturing. This practice is partly driven by the fact that the standard quality of materials required for production can only be satisfied by European suppliers. Another driver for centralised purchasing is to gain economy of scale and quantity discounts.

4.3.2 Co-ordination of manufacturing companies in Indonesia

This section will explore how real international supply networks link and integrate the activities conducted by different elements in the supply networks. In exploring the co-ordination of each international supply network several issues are considered, including:

- The decoupling point strategy
- What activities need to be co-ordinated?
- Are the activities co-ordinated locally, regionally or globally?
- What information is shared between elements in the supply networks?

Table 4.4 summarises findings on co-ordination aspects gathered from the case companies.

4.3.2.1 Decoupling point strategy

A company's decoupling strategy is considered as one aspect of co-ordination because it determines the flow of information across elements in the supply network. As shown in table 4.4 all the contract manufacturers conduct their processes based on customer order. Therefore, the contract manufacturers only start their production after the buyers place their orders.

Table 4.4 Co-ordination of international supply networks

Characteristics	SHOES	ASIA_BULB	EURO_BULB	FOOD	SILICA	HEATEX	FASHION_WEAR	CASUAL_TWO	CASUAL_CON	FISH	FURNITURE
Types of Process	Batch Manufacturing	Batch Manufacturing	Batch Manufacturing	Continuous Manufacturing	Continuous Manufacturing	Job Shops	Batch Manufacturing	Batch Manufacturing	Batch Manufacturing	Flow Shop	Job Shops – Batch Manufacturing
Decoupling Point Strategy	Supply Chain: Make to Stock Subsidiary: Make to order	Supply Chain: Make to Stock Subsidiary: Make to order	Supply Chain: Make to Stock Subsidiary: Make to order	Supply Chain: Make to stock Subsidiary: Make to order	Supply Chain: Make to stock Subsidiary: Make to order	Make to Order	Make to Order	Make to Order	Make to Order	Make to Order	Make to Order
Co-ordination Mechanism	Centralisation Formalisation Planning Output Control Informal co-ordinations	Centralisation Formalisation Planning Output Control Informal co-ordinations	Centralisation Formalisation Planning Output Control Informal co-ordinations	Centralisation Formalisation Planning Output Control Informal co-ordinations	Centralisation Formalisation Planning Output Control Informal co-ordinations	Centralisation Formalisation Planning Output Control Informal co-ordinations	Meeting, Communication, Output Control	Meeting, Communication, Output Control	Meeting, Communication, Output Control	Meeting, Communication, Output Control	Meeting, Communication, Output Control
Information Shared	Forecast Capacity Shop floor information	Forecast Capacity	Forecast Capacity	Forecast Capacity	Forecast Capacity Regional customer need	Forecast Capacity Regional customer need	Production progress in the shop floor	Production progress in the shop floor	Production progress in the shop floor	Production progress in the shop floor Technical support	Production progress in the shop floor

HEATEX is the only subsidiary of the MNC supply network that works in a make-to-order environment. The rest of MNC supply networks work in make-to-stock environment. However, the operations of the MNC subsidiaries are based on production order and forecast provided by their internal customer (headquarters or regional offices). In this environment, some of the operation is conducted based on the forecast.

4.3.2.2 Co-ordination mechanism

According to Martinez and Jarillo (1991), co-ordination mechanisms in MNC corporations can be divided into formal and informal. Formal co-ordination mechanisms include centralisation, formalisation, planning, output control and behavioural control. The informal co-ordination mechanism consists of three managerial tools: lateral relations, informal communication and organisational culture.

The extent of the co-ordination activities varies across different companies particularly between companies belonging to MNC supply networks and those belonging to contract manufacturer supply networks. All types of formal and informal co-ordination mechanisms suggested by Martinez and Jarillo (1991) are found in the six companies belonging to MNC corporations. In general, the co-ordination between elements in the contract manufacturer supply network is conducted through meetings, communication and output control. However, no formalisation, centralisation or joint planning mechanisms are found between buyer and contract manufacturers.

4.3.2.3 Co-ordination of value chain activities and information shared

In most of the contract manufacturer supply networks, except FISH, co-ordination between the contract manufacturer and their buyers typically take place in the sampling process. In addition, buyers may also order certain types of materials and therefore co-ordination is necessary in procuring the right materials. When an order has been placed and material is agreed, the buyer does not tend to get involved in production. However, the buyer will do a second quality check on the finished garments. The evidence also highlights that there is very little information sharing between elements in the contract manufacturer's supply network.

Overall, more co-ordination efforts in conducting value chain activities are found between elements in the MNC supply network. However, findings with respect to what value chain activities are co-ordinated locally, regionally or globally vary across the six MNC networks.

As suggested previously, two companies that produce intermediate (industrial) products namely HEATEX and SILICA act as the sole subsidiary of their respective network in the Asia Pacific Region. The two subsidiaries deal directly with the customer and manage their demand. HEATEX works in a make-to-order environment. Thus, HEATEX starts planning their production when they receive an order from the customer. SILICA on the other hand works closely with their main customer. The company and their major customer established a long-term contract. The customer provides SILICA with a yearly forecast of their material requirements. This is considered by

SILICA as a yearly production plan that is broken down into monthly plans. On a weekly basis the customer will send a confirmation order. Despite having more autonomy to deal with their customer, HEATEX and SILICA still maintain co-ordination with their head office. They reported the knowledge that they found in serving the customers in the region and share it with subsidiaries serving different regions. In some cases, the headquarters also re-allocates demand that cannot be satisfied by subsidiaries in different regions.

In ASIA_BULB case, close co-ordination between the company and the headquarters take place in the sampling process where designs developed by headquarters are 'tested' in the company. Since ASIA_BULB does not deal directly with the marketing of their product, the corporate headquarters provide them with 'rolling forecast' information. The information consists of confirmed production orders for the next month and forecasts of future demand. The forecast of future demand is used by ASIA_BULB to plan its medium-term capacity and resources including buying materials. Although ASIA_BULB has great autonomy to choose its suppliers, the materials have to satisfy standard requirements determined by headquarters and therefore ASIA_BULB has to co-ordinate procurement problems with headquarters. Finally, ASIA_BULB has to keep headquarters informed regarding shipment of finished products to the end customers.

EURO_BULB's supply network has several subsidiaries in the Asia Pacific region to satisfy the regional market. Sales and marketing activities in each country are managed by a national commercial organisation. The national commercial organisation reports sales information to the Asia Pacific regional office. The regional office manages the demand in order to ensure a balanced load across subsidiaries in its region. ASIA_BULB receives production order and demand forecasts from the regional office. FOOD supply network also has several subsidiaries in the Asia Pacific region. Each subsidiary produces several core products for the regional market. Sales and marketing activities are handled by a *supply planner*. The supply planner determines a weekly production plan and sends it to FOOD to be executed.

The SHOES supply network is found to be a special case. While the rest of the supply networks investigated in this study show a product-based structure, where each subsidiary produces certain types of product, SHOES' supply network is structured based on processes. SHOES only conducts one stage of the manufacturing process, i.e. producing shoe uppers, while the finishing operations are conducted in different manufacturing units (sister companies) within the group. In addition, the shoe manufacturer is the only case where the products are entirely sold in foreign markets. Thus, SHOES appears to be the most globally oriented among the six MNC supply networks (McGrath & Bequillard, 1989).

SHOES' supply networks show tight linkage and co-ordination among members of the supply chain. SHOES has to co-ordinate with headquarters or other elements of the network in conducting most activities. Design and development activities are conducted globally by corporate headquarters. However, SHOES is actively involved in the product development process by giving feedback on the manufacturability of the design. SHOES starts production based on the production order allocated by headquarters. At the same time, the headquarters also provide medium-term forecasts of demand so that SHOES can plan their resources. SHOES also has the autonomy to choose the right supplier provided that it satisfies strict standards of materials set by headquarters. SHOES continuously communicates the production progress to sister companies as their direct customers. Any delays or problems in the production of shoe uppers have to be reported to other elements, as it will affect the subsequent processes. SHOES' supply networks are linked with advance communication and information technology so that all information such as demand, forecast or capacity can be shared by elements across the network.

4.3.2.4 Nature of relationships

As expected, none of the contract manufacturers involved in this study have 'formal' long-term contract or commitment with any particular buyer. However, each contract manufacturer has a regular buyer that has placed several orders throughout the time. Even with the regular customers, contract manufacturers have to follow the procedure commonly found in contractual relationships including making samples for production, price and due dates negotiation etc.

4.3.3 Grouping the MNC supply networks

The six manufacturing companies belonging to MNC can be grouped according to similarities and differences in their configuration and co-ordination aspects.

4.3.3.1 Regional autonomous subsidiary

HEATEX and SILICA are characterised by the presence of regional autonomous subsidiaries. As shown in figure 4.2, both networks consist of subsidiaries that produce intermediate products for other companies in a certain regional market. In these industries close contact with customers is necessary. This particularly applies to HEATEX that produces based on customer order. As a result, subsidiaries are given the authority to deal directly with their customers in order to be responsive to customer needs. This explains why SILICA and HEATEX appear to have more autonomy over their operations compared to other subsidiaries involved in this study.

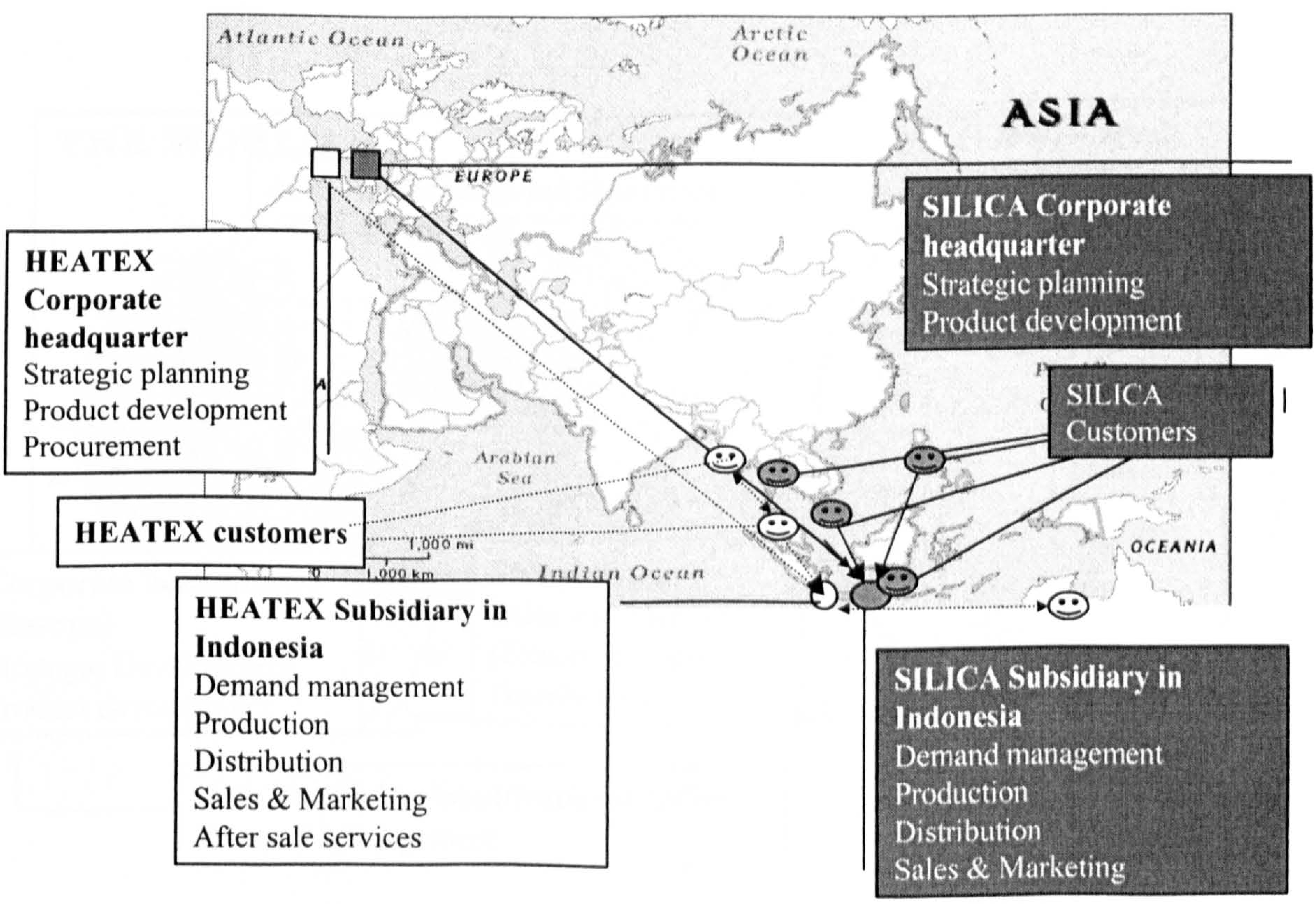


Figure 4.2 Supply network with regional autonomous subsidiaries

4.3.3.2 Regional clusters of subsidiary

Figure 4.3 illustrates the second group of MNC supply networks. The ASIA_BULB, EURO_BULB and FOOD supply networks are characterised by the presence of several subsidiaries in a certain region to satisfy regional or global markets.

The network has a wide range of product lines and deploys the production of certain product lines to a 'focus factory' as suggested by Child et al. (1991) and Milgate (2001). Thus, each subsidiary produces a certain range of products. A great deal of exporting and importing of finished products across subsidiaries in the region are found in this group of supply networks.

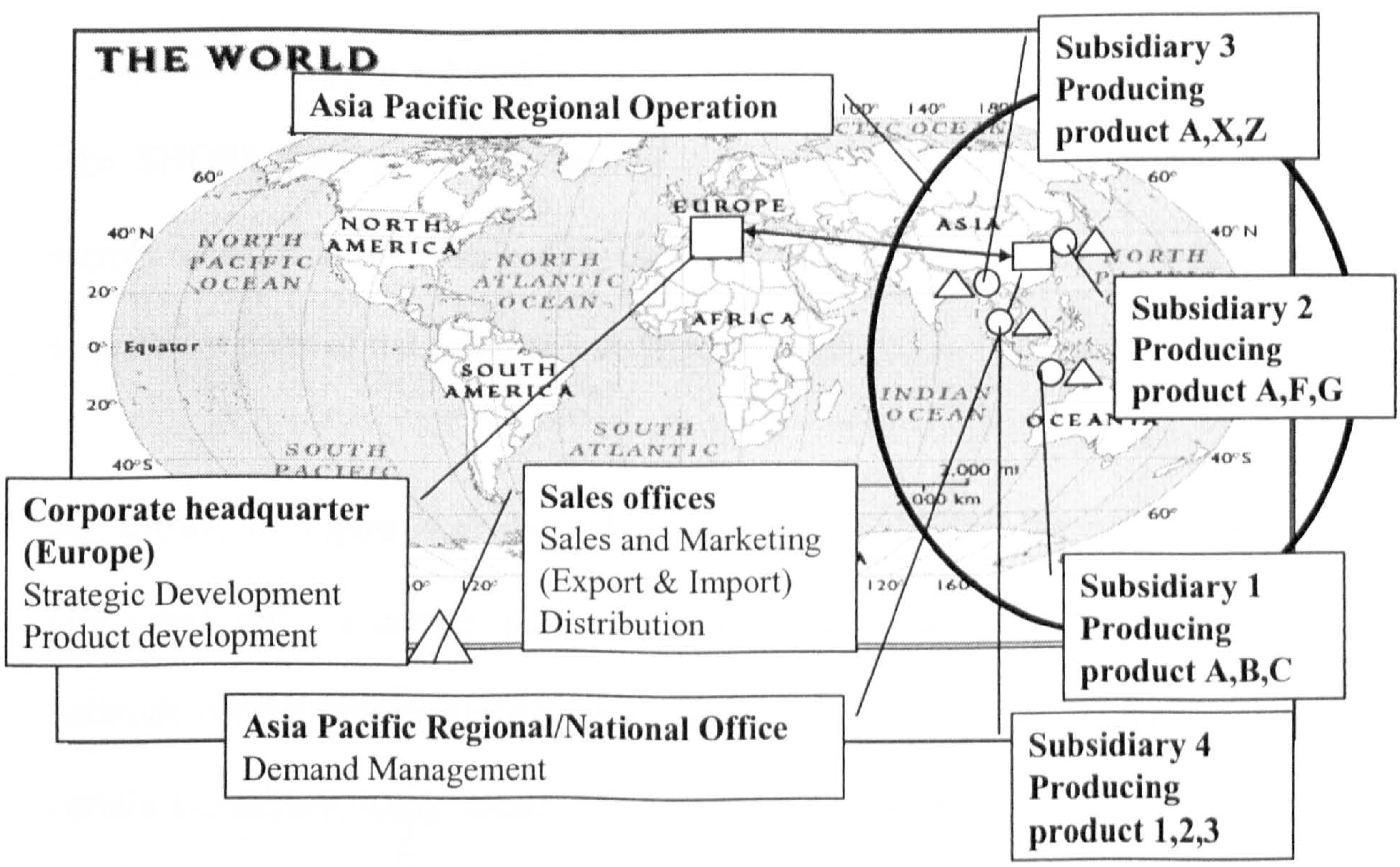


Figure 4.3 Supply network with regional clusters of subsidiaries

Interesting facts were found in ASIA_BULB and EURO_BULB. Unlike the FOOD's supply network where each subsidiary has distinctive product and process competencies, the product and process technology in the light bulb manufacturers in general are quite similar. Thus, there are certain products in the two light bulb manufacturer networks that can be produced in several manufacturing units. This allows the two networks to switch production of a certain product to another subsidiary when there is a problem such as shutting down of factories, strikes, capacity shortage etc. in one of their subsidiaries.

These two networks have regional organisations that monitor and attempt to manage or consolidate demand and ensure a balanced capacity load across subsidiaries in the respective regions.

4.3.3.3 Global supply network

The SHOES supply network applies a pure global strategy. The SHOES supply network is characterised by the presence of several subsidiaries spread in different parts of the world to satisfy global market.

As shown in figure 4.4, the subsidiary in the SHOES supply network conducted only a certain stage of manufacturing activities, while other network configurations assign the production of a range of products to a certain subsidiary. They locate value chain activities in the best facility to capitalise on location specific advantages, such as specific labour ability or low labour cost, and tightly co-ordinate activities globally.

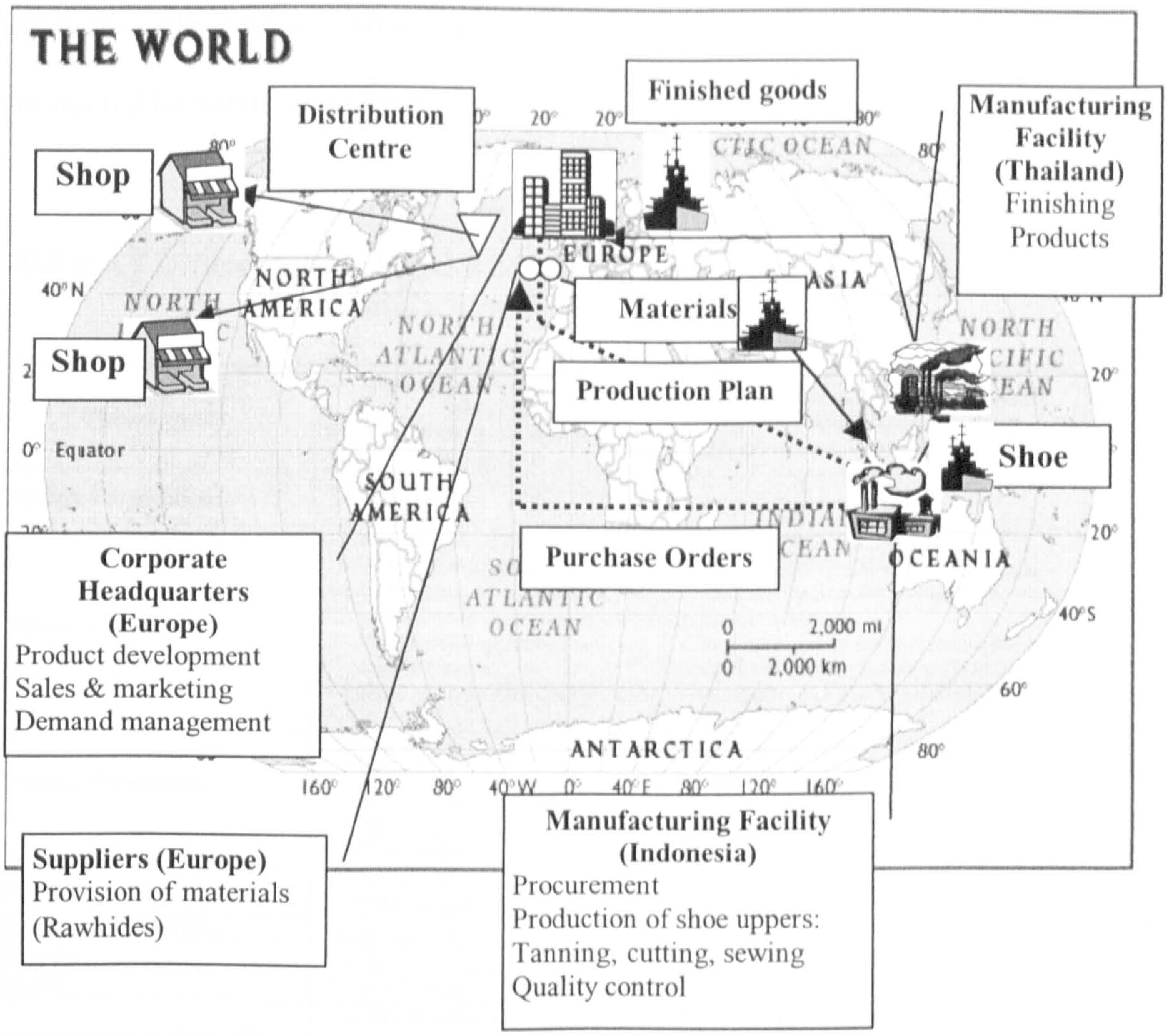


Figure 4.4 Global supply network

4.3.4 Comparison between MNC and contract manufacturer supply networks

Based on the previous analyses, considerable differences are evident between the configuration and co-ordination of MNC supply network and contract manufacturer supply network. Several important differences are presented in table 4.5.

The choice of establishing a foreign subsidiary (owning a facility) or contracting to a foreign partner appears to be influenced by the product and industry characteristics. Contract manufacturers produce less sophisticated products with low technological content. On the other hand, production conducted by MNC subsidiaries has higher technological content.

Table 4.5 Different characteristics of Multinational Corporation and contract manufacturer supply networks

Characteristics	Multinational Company – Subsidiary (Network under common ownership)	Brand Owners/Retailers - Contract Manufacturer (Network under different ownership)
Product Characteristics	- Higher degree of technological content	- Low technological content
Nature of Industry	- Some degree of capital investment required - Development in product & process technology through time - Combination of manual and machine works - More certainty over the business	- Relatively low capital investment - Mature industry (Slow development in product/ process technology) - Labour intensive - High uncertainty in the business due to rapid changes in market preferences & seasonality in demand (particularly apparel)
Strategic Orientation	- Low cost - Reliability - Market responsiveness - Flexibility	- Low cost - Flexibility
Focal elements in the supply network	- Headquarter - Subsidiaries - Other subsidiaries	- Brand owners/ retailers/buyer - Trading agency - Contract manufacturer
Elements through time	Relatively static	Dynamically changing
Suppliers	Foreign	Local & Foreign
Market	Local & Foreign	Foreign
Configuration of Value Chain Activities	The supply network focuses on delivering products/services to the customer from research development to sales & marketing	Retailers/buyer focuses on front and end of value adding activities (R&D and Sales & Marketing) while contract manufacturer handle the manufacturing aspect
Degree of co-ordination	More co-ordination effort	Limited co-ordination effort
Nature of relationships	Long term	Short term & contractual relationships

Contract manufacturers involved in the industries, which are labour intensive, mature with slow development in product and process technology. There is also great uncertainty in the business in the long-term. All these characteristics caused great emphasis on achieving low cost while maintaining flexibility.

Another difference is found when we compare the supply base and the market of MNC supply network and contract manufacturer supply network. MNC supply networks procure materials from a foreign supply base to produce product for local, regional and global markets. On the other hand, contract manufacturers use local suppliers extensively to produce products for foreign buyers.

As the MNC supply network to some extent owns most of the elements in its supply network, the structure of elements such as manufacturing unit, sales organisation, corporate headquarters, distribution centers etc. is more stable and to a certain period can be considered as 'static'. In the contract manufacturer supply network, focal elements including buyer, supplier, intermediaries etc. are independent organisations with no long-term commitment among them. Therefore, the configuration of the contract manufacturer supply network may continuously change from one period to another. The configuration is much more 'dynamic' as elements, that are part of the supply network in one period, may not be involved the supply network in the next period.

In the MNC supply network, dispersal of value chain activities to different elements is supported by close co-ordination across elements in the network. Important information including, demand, forecast, capacity and market intelligence information are made available across elements involved in MNC supply network. In contract manufacturer supply network, there is a clear division of role and activities. Retailer or brand owner, as the buyer, concentrates on conducting design and development, distribution, sales and marketing activities. The contract manufacturer primarily focuses on manufacturing activities. The nature of relationships is contractual with no long-term commitment between elements in the contract manufacturer supply network. Following order placement and negotiation processes, there is very little information sharing between buyer and supplier except for reporting progress.

4.3.5 Configuration and co-ordination of INTIMATE_WEAR network

The previous section has discussed findings from MNC and contract manufacturers' international supply networks. In this section, findings from an MNC that owns manufacturing units as well as using foreign contract manufacturers are discussed.

4.3.5.1 Configuration

INTIMATE_WEAR produces various products such as bras, knickers and nightwear, referred to as intimate products. The INTIMATE_WEAR supply network is shown in figure 4.5. The INTIMATE_WEAR supply network consists of several manufacturing facilities and contract manufacturers (also called offshore manufacturers).

The INTIMATE_WEAR private brand operations are influenced greatly by their customer. The customer is involved in various parts of the value chain activities from design and development of product and demand management. The customers are primarily based in the UK. INTIMATE_WEAR facilities are located in the UK and neighbouring countries in order to maintain close contact with their customers. The commercial team is co-located with the customer's headquarters. However, high labour cost in the UK forces INTIMATE_WEAR to move the labour-intensive activities (cutting and sewing) to Northern Ireland and Morocco, where costs are relatively cheaper and geographically close to the UK. In addition to producing in-house, INTIMATE_WEAR also uses contract manufacturers in Turkey, Indonesia and Sri Lanka to conduct approximately 20% of their production.

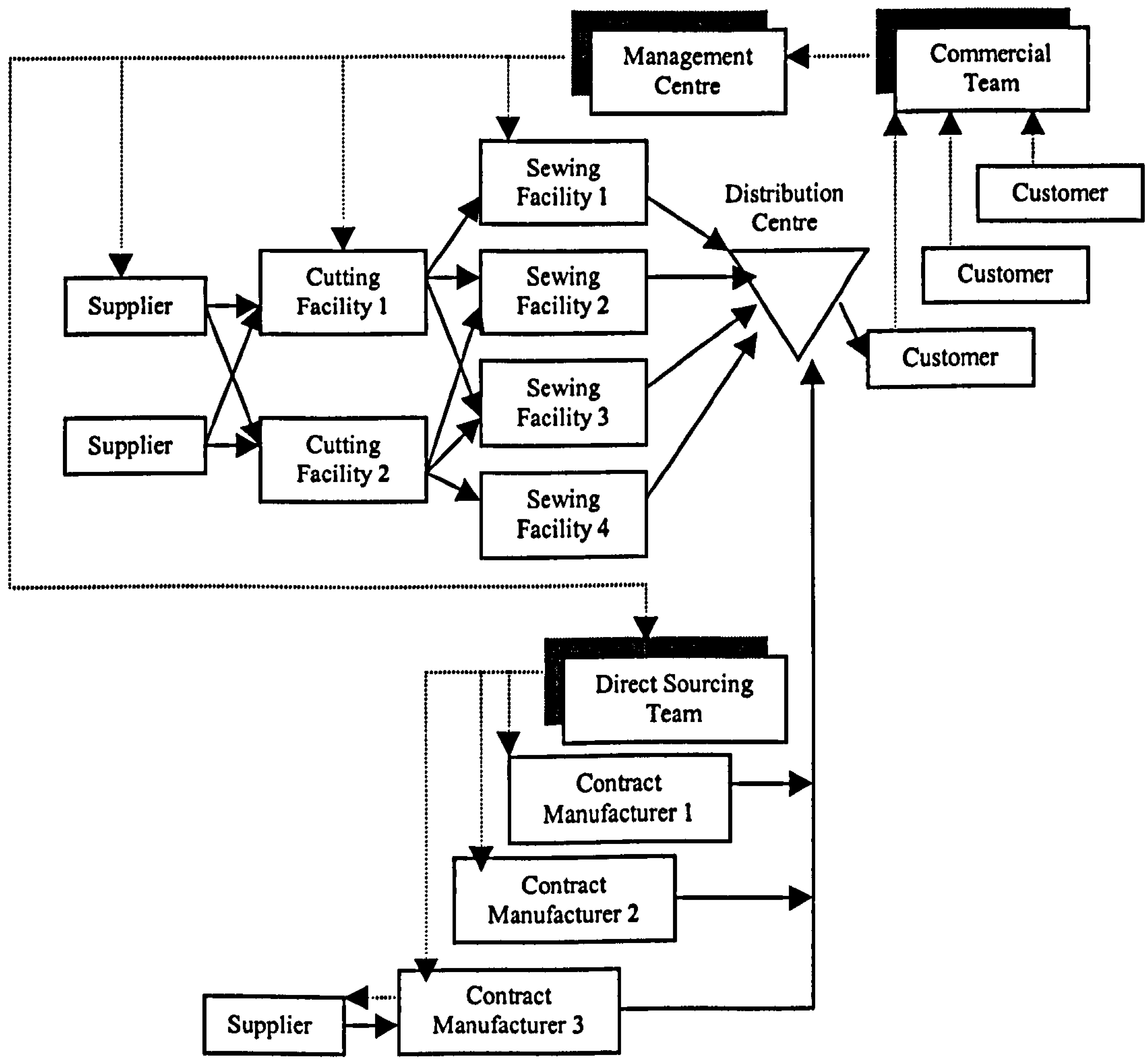


Figure 4.5 Configuration of INTIMATE_WEAR supply network

4.3.5.2 Demand management and production allocation

INTIMATE_WEAR works closely with their customer in determining the business plan that drives the operations. The account managers and customer determine the yearly sales anticipation. This sales anticipation gives INTIMATE_WEAR a strategic view of what the business is likely to be in the next 12 months and allows them to plan the capacity required to fulfil the anticipated demand.

The rolling 12 months sales forecast is usually broken down into shorter time scale associated with the customer selling seasons or launch activities. A commercial team from INTIMATE_WEAR and customer have to work on the range of products that they will produce for a certain selling season. In this process they define what styles of product to be produced within various ranges of products, the colour palette for each range, what materials to be used etc. For new products or ranges of products, the technical team from INTIMATE_WEAR will be involved in developing the materials, finding suppliers, working with suppliers in fabrication of the material, testing or 'trial and wear' the material when necessary, etc. The whole new product development activities are on going process held prior to the launch period.

Following the discussion between the customer and commercial team a 12 months demand requirement is generated. This may consist of:

1. **Firm orders:** referring to products that the customer requires complete with information on launch volume, volume per week and completion date. Customer has to take the responsibility for any changes/cancellation in these orders.
2. **Grey fabrics:** the customer may decide to book grey fabrics for relatively long lead-time materials such as fabric for night wear (embroidery). In this case, the fabric is knitted and made but it can be dyed to any colour, which will give the customer more flexibility to decide the coloration.

3. **To be confirmed (TBC):** which is basically a sales anticipation but the customer is not committed to this number, so they can cancel or amend this at any time.

The demand requirement can be produced in the company's own unit or sourced from offshore manufacturers. The decisions to conduct the production in company-owned manufacturing sites or to buy them from offshore manufacturer are defined at the strategic level within the sales environment. One of the main considerations is the availability of raw material close to the production unit. The costs associated with fabrics and components constitute 40 - 50%, in comparison to labour costs that count for 15% of the overall cost. Therefore, the availability of materials with acceptable price and quality close to the production unit is vital for INTIMATE_WEAR allocation decision. The decision to produce offshore, which clearly has advantages in terms of cheaper labour cost, may not be justifiable without the presence of a capable supply base that will provide the operation unit with the required materials.

Once demand requirements are allocated, the operations in company-owned facilities and contract manufacturers are managed by different management teams in the company. The production in the company's subsidiaries is managed by several functions in the INTIMATE_WEAR management centre including planning and purchasing. On the other hand, the Direct Sourcing Team handles the management of contract manufacturers in Indonesia, Sri Lanka and Turkey.

4.3.5.3 Co-ordination of operation in company's own manufacturing units

The INTIMATE_WEAR planner uses the business anticipation to plan their capacity requirements for the next 12 months. The planner will start planning at a product level and try to associate the sales anticipation with a style or various styles within a product range. The first 12 - 13 weeks of the plan will be filled with firm orders, and the rest of the planning horizon is very much a forecast, which will need confirmation from the customer. The planners develop a monthly style-colour plan that consists of the volume of production and due dates. Then, based on the input of size ratio/proportion provided by customer, the planner uses an established system to dictate the weekly style-colour-size plan. This style-colour-size plan is reviewed continuously every week. This plan is passed back to the customer service team, who will present it to the customer to be signed-off. This plan also acts as schedule for operations.

As noted previously, in INTIMATE_WEAR business the costs of materials and procurement count for almost half of the manufacturing costs. For the manufacturing sites in the UK and Morocco, about 90-95% of the materials that they use for production come from Western European suppliers in Germany, Italy, UK and Spain. The commercial team and customer define the standard quality of material used in production.

4.3.5.4 Co-ordination of contract manufacturers

INTIMATE_WEAR are engaged in a long term basis with several contract manufacturers. The contract manufacturers in Turkey, Sri Lanka and

Indonesia respectively produce dressing gowns, packed briefs and range of bras for the company. The factory in Turkey is vertically integrated so they can produce their own fabrics. A contract manufacturer in Indonesia is also vertically integrated as they can produce most materials from fabrics to hooks and eyes in the same factory. The contract manufacturer in Sri Lanka is not vertically integrated, but procures the majority of their materials from local suppliers.

In managing these factories, a direct sourcing team is divided into three areas:

1. Business development which deals with supply base/materials, developing new products and allocating them to different factories. They are also in charge of pre-work activities in terms of costing and price negotiation with supplier.
2. Technical team which works closely with business development team in deciding which factories are the best to produce the products. They are also in charge of 'auditing' the factory and setting up the procedure to conduct the operations. They sometimes set up the production line for difficult products. The technical team regularly visits these factories to monitor their performance.
3. Sourcing, who is responsible to monitor the order fulfilment process. Each factory has an account manager who deals with the orders, monitors production every week and manages the critical path.

All the contract manufacturers have their own planner, merchandisers, buyers, cutting room and technical teams. INTIMATE_WEAR direct sourcing team provides these factories with a 12 month rolling plan, which gives them the foresight of the capacity (volume) that INTIMATE_WEAR will require from them within the period. The first month of the plan is given in standard hours required. On the following month, INTIMATE_WEAR direct sourcing team will place a purchase order (stating the style, contract volume which may go up and down from the initial forecast) and due dates. At the same time, INTIMATE_WEAR will also provide a forecast for the following months. This is done continually. There is no formal contract and INTIMATE_WEAR made no commitment to this forecast.

As these factories conduct almost all the operations (from purchasing until packaging), the role of the direct sourcing is mainly to monitor or audit the performance of this factory. Performance is measured in terms of style-colour-quantity produced in a certain period and is compared against the plan. At the beginning of the week the factories have to send out a report of shipments made in the previous week. INTIMATE_WEAR also receives a report on what is happening in the cutting room, production line, what materials have come in etc. on a weekly basis. In this way, the direct sourcing team has the visibility of what is happening in the offshore factories. They also keep up to date information on the critical path activities (when the fabric needs to be agreed or signed off, when they should know the packaging information etc). Communications between direct sourcing team and offshore manufacturer is done via e-mails and weekly conference calls.

4.3.5.5 Summary of INTIMATE_WEAR configuration and co-ordination

INTIMATE_WEAR configuration offers several advantages. INTIMATE_WEAR ensures reliability over the production by owning several manufacturing facilities. Locating the production geographically close to the customer also enables them to be more responsive to customer needs. The manufacturing unit in the UK enables them to ramp-up production in reaction to customer's selling pattern. At the same time, INTIMATE_WEAR obtains cost advantages and flexibility from their network of contract manufacturers. The contract manufacturers offer lower production cost compared to production in INTIMATE_WEAR manufacturing unit. Working with offshore manufacturers also enables the company to obtain scale advantages and to some extent also 'scope' advantages without committing to fixed cost associated with owning the capacity. As a result, INTIMATE_WEAR has more flexibility as they share some of the risks of demand uncertainty with other parties.

However, the complexity of INTIMATE_WEAR configuration means that intensive co-ordination has to be dedicated to integrate their supply networks. Intensive coordinative efforts are found in the operations of company-owned units as well as contract manufacturers. Unlike the cases in the contract manufacturers in Indonesia, where buyer and suppliers work in traditional arms-length relationships with very little co-ordination effort, INTIMATE_WEAR appears to work in a more collaborative relationship with their offshore manufacturers. Although they do not have long-term contracts with the contract manufacturers, they provide them with forecast information.

They are also actively involved in technical activities such as setting up a production line for new products and regularly visit the manufacturers.

The different nature of relationship found between INTIMATE_WEAR and its contract manufacturer compared to a contract manufacturer supply network appears to be influenced by the level of expertise and therefore value offered by a contract manufacturer. Each of INTIMATE_WEAR's contract manufacturers has competencies to produce a certain range of products that satisfy their standard quality. Therefore, INTIMATE_WEAR may want to maintain their working relationship instead of changing to other suppliers as it means that they have to start the new relationships that might incur high transaction costs.

4.3.6 Implications of configuration and co-ordination strategies on the operations of international supply networks

The configuration of an international supply network influences the co-ordination of activities across elements in the network (Meijboom and Vos, 1997; Meijboom, 1999). Meijboom (1999) highlights functional splitting as one of the main challenges when subsequent activities are conducted by different elements in the chain. Separating activities across different elements in the supply chain means that more co-ordination effort has to be dedicated to ensure a smooth flow of information, materials and products across different elements in the supply network.

This is particularly evident in the SHOES case. The SHOES global supply network is characterised by complex flow of materials and information across the element in the supply network. Thus, a tight co-ordination to ensure a smooth flow of materials and information across different stages is found in this supply network.

INTIMATE_WEAR configuration is also very complex. Sometimes subsequent manufacturing activities are conducted in different facilities, for example cutting of materials is conducted in Northern Ireland and sewing is conducted in Morocco, Turkey or Tunisia. As a result, tight co-ordination and control in each stage of the value chain activities is found in INTIMATE_WEAR supply network. INTIMATE_WEAR and the customer have what they call Critical Path Management to ensure there is no delay in operations and that every party has critical information required to meet the customer demand at the right time. INTIMATE_WEAR also closely monitors the operations conducted by their contract manufacturer through the direct sourcing team.

The rest of the MNC supply networks (ASIA_BULB, EURO_BULB, FOOD, SILICA and HEATEX) have less complex configurations. Although the operation of manufacturing companies in Indonesia depends on the materials bought from foreign suppliers, the companies conduct the entire manufacturing processes. As a result, the operation of each subsidiary is relatively independent from other subsidiaries. The co-ordination of these MNC supply networks is not as intense as the co-ordination of SHOES supply networks.

4.3.7 Product variety

4.3.7.1 Factors generating product variety

The empirical study also investigated the issue of product variety facing real international supply networks. Companies involved in this study produced different types of products. Therefore, the first product variety analysis provided here identifies the factors that differentiate product variants in each case company i.e. factors that generate product variety. Table 4.6 shows various factors that generate product variety in each case company.

Five of the case companies i.e. SHOES, INTIMATE_WEAR, FASHION_WEAR, CASUAL_TWO and CASUAL_CON, produce different types of apparel products. Apparel product variety is generated considerably by consumer-specific factors such as gender and age, as well as fashion. The appearance (aesthetics) of apparel products is as important as their functionality. As a result, style, size, materials and accessories are several factors that differentiate apparel products. In contrast, chemical is an intermediary product used in the manufacture of consumer care products. SILICA only offers two main products, namely abrasive and thickener chemicals, differentiated by the chemical content. In FISH case, customers buy processed fish to be used as ingredients in subsequent food manufacturing. Variation in the processed fish is due to different types of processing (peeled, cooked, etc). FOOD offers various types of product differentiated by several factors such as nutritional content, flavour and packaging.

Table 4.6 Factors generating product variety and their effect on supply chain operations

Companies	Factors generating product variety	Supply chain operations affected			
		Procurement of Materials	**Process**	**Major Set-ups**	**Minor Set-ups**
SHOES	Materials	Different leather: types, pattern, color	Material preparation (tanning leather)	Resetting facilities	-
	Style & size	Volume of materials required	Cutting & sewing	Changes in styles (setting up the entire line)	Changes in sizes and color
	Accessories	Require different parts (accessories)	Sewing		Changes in accessories
ASIA_BULB & EURO_BULB	Bulb: Shape, size (diameter)** **) For ASIA_BULB there are also different shades of bulb as source for variety	Glass	Bulb making (continuous production)	Resetting facilities	-
	Functionality & electrical attributes (Voltage & Wattage)	Different electrical components	Assembly	- Changes from high to low voltage - Changes from big bulb diameters to small	Changes of wattage or coil
	Different packaging	Different packaging materials	Packaging		Changing to different packaging
FOOD	Different product types (function and nutrition content) & Different flavor in each product types (vanilla, chocolate, etc)	Relatively not affected	Entire process	Cleaning the entire production line	Not Applicable
	Different packaging	Different packaging materials	Packaging		Changing to different packaging
SILICA	Chemical contents	Relatively not affected	Entire process	Cleaning the entire production line	
HEATEX	Type of heat exchanger & Dimensions	Different heat exchanger components	Entire process from drawing–fabrication	Not Applicable	
FASHION_WEAR	Main Materials: types & color	Different yarn	Material preparation: knitting the yarns into fabrics, cutting	Resetting facilities	
INTIMATE_WEAR, CASUAL_TWO & CASUAL_CON	Main Materials: types, pattern, color	Different fabric: types, color, patterns	Material preparation: cutting	Resetting	
FASHION_WEAR, INTIMATE_WEAR, CASUAL_TWO & CASUAL_CON	Style & size	Volume of materials required	Cutting & sewing	Changes from one style to another (require training) & setting the line	Changes in sizes and color
	Accessories	Require different accessories (unique materials)	Sewing		Changes in accessories
FISH	Different processing	Different size of raw material	Entire process	Setting up the entire production line	Not Applicable
FURNITURE	Material	Different types of wood	Kiln dry	Resetting facilities	
	Functionality (Indoor, Outdoor)		Preparation of materials (cutting, dividing, moulding), Processing	Changes in different type of product	-
	Style	Accessories (handle, glass etc)	Assembly		Changes in different accessories

FURNITURE produces different types of furniture according to customer orders. The furniture varies on many factors including materials, functionality (indoor, outdoor and bedroom) and style. HEATEX produces heat exchanger system to be used as part of cooling systems in food manufacturing, office or public facilities. The heat exchanger is mainly differentiated based on the type of heat exchanger. However, it is highly customised to fit customer specification particularly with respect to the shapes and dimensions of the product.

Interesting results are found in the light bulb manufacturer case. Light bulbs are mainly differentiated based on functionality and electrical attributes. However, ASIA_BULB recognised the advantage of introducing *aesthetics in light bulbs* as additional attributes to differentiate their product over their competitor. Therefore, ASIA_BULB starts to produce various types of light bulb (different colour, shades, shapes etc.) in order to gain wider market share.

4.3.7.2 Level of product variety

Having identified the factors causing product proliferation, we analyse the level of product variety produced by each company. The level of variety is classified into simultaneous and sequential variety, a classification widely used in product variety literature (Anderson, 1995; Fisher et. al., 1999). Information is obtained from the case companies in terms of the number of different products that they produce at a given time (simultaneous variety) and the rate at which they replace existing products with new products (sequential variety).

The relative level of simultaneous and sequential product variety offered by the case companies is captured in figure 4.6. In several cases, the level of simultaneous variety produced by the company is equivalent to the sequential variety. SILICA and FISH both have very low sequential and simultaneous variety relative to the other case companies. FISH produces a maximum of six different types of processed fish at a given time and the type of products remains the same from time to time. Similarly, SILICA produces very low product variety at a given time with a low rate of new product introduction relative to other companies involved in this study. FOOD produces wider range of product variants compared to SILICA and FISH in a certain period. They offer condensed and instant milk with different nutritional content in different flavours and various packaging. FOOD also introduces more new products over time compared to SILICA and FISH.

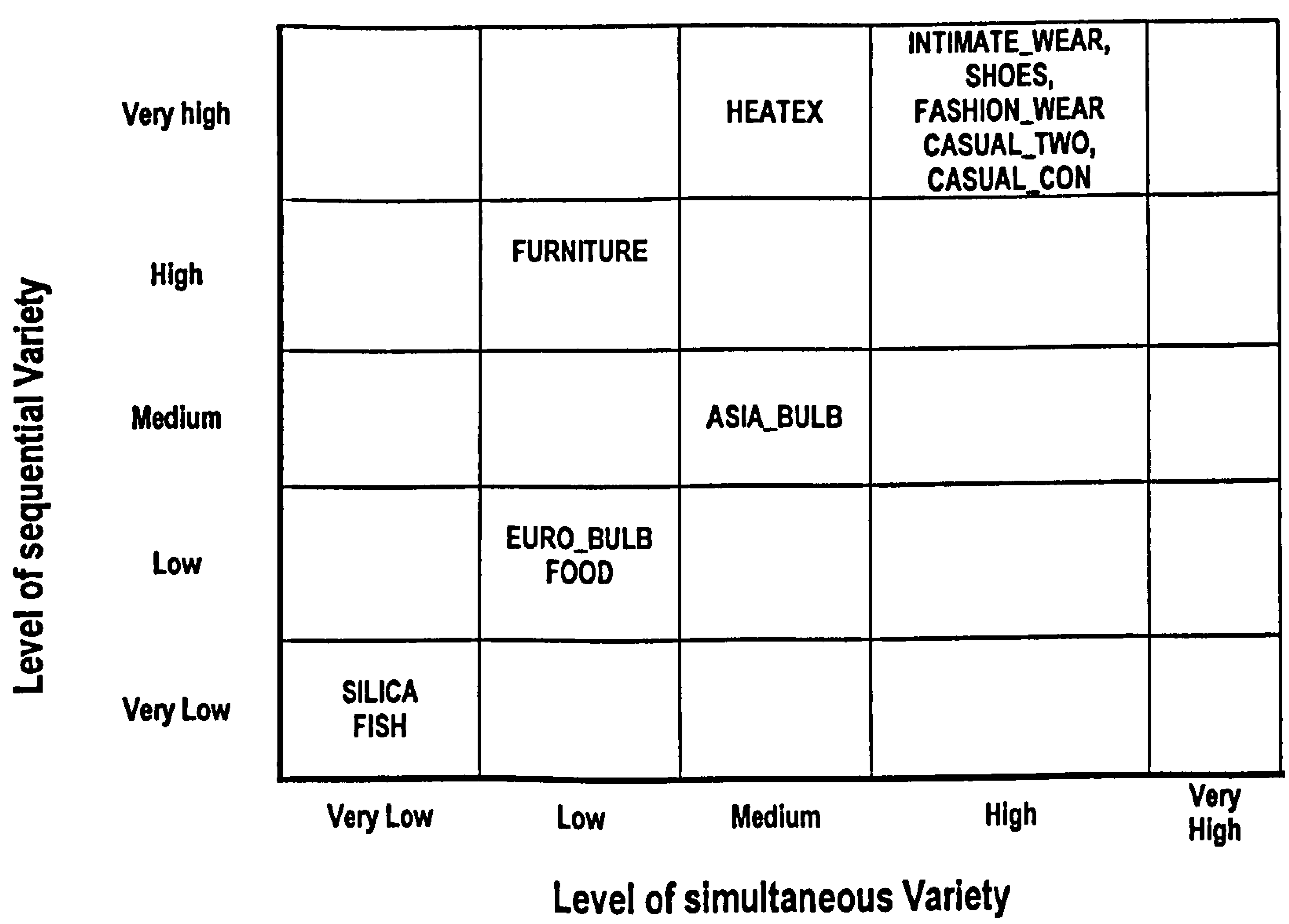


Figure 4.6 Simultaneous and sequential variety in each case company

As highlighted previously, interesting findings are found in the two light bulbs manufacturer cases. EURO_BULB produces dozens of product variants differentiated mainly by functional electrical attributes (wattage & voltage). The rate of new product introduction over time is relatively low. Thus, EURO_BULB has low simultaneous and sequential variety relative to other companies in the study. ASIA_BULB introduces other sources of variety in their product. They offer different shapes, shades and colours of light bulbs to differentiate their products. As a result, ASIA_BULB has a higher level of simultaneous and sequential variety relative to EURO_BULB.

Some of the case companies have an unequal level of sequential and simultaneous variety. These companies, which include FURNITURE, HEATEX, SHOES, FASHION_WEAR, CASUAL_TWO and CASUAL_CON all have higher level of sequential variety relative to simultaneous variety. FURNITURE produces a low level of variety at a given time due to limitations in their capacity. However, the rate of new product introduction is high as their customer preferences change rapidly from season to season. HEATEX produces a medium level of product variety in a certain period of time. However, the fact that their product is customized to specific customer needs (sizes, shapes) means that the sequential variety produced by HEATEX over time is very high (new customer means new product).

Five companies involved in the apparel business produce a high level of simultaneous variety. In a certain period SHOES produces various ranges of leather shoes – casual, men's, ladies, shoes, kids, sports. Each range of product is differentiated further into different styles, colors and sizes. As a result, SHOES produces hundreds of different product variants at a given time. SHOES introduces new product designs for each selling season thus the level of sequential variety is very high. Similarly, the three garment manufacturers produce a great variety of products in a certain period and introduce new design of clothes for the new selling seasons.

INTIMATE_WEAR produces different range of products for their customer such as Shape Wear, Control Wear etc. One range might comprise of various combinations of product styles such as bras, knickers or nightwear. A certain style of product will be made in different colours (from black, white and cream as standard colours to more 'fashionable' colours such as lilac, pink etc.) and all in a range of sizes. Taking into consideration all the variation in range, style, colour and size, INTIMATE_WEAR can produce thousands of different items simultaneously.

4.3.7.3 Supply chain operations affected by product variety

Table 4.6 shows that different factors that generate product variety affect different operations of the supply network. In most cases, product variety affects the procurement of materials. In the apparel and furniture cases, different materials create product variety directly. For example, CASUAL_TWO offers different styles of casual wear made from jersey or lycra. The furniture produced by FURNITURE can be made from pinewood or timber.

In ASIA_BULB and EURO_BULB cases, producing product variants with different electrical attributes means that they need to procure different types of electrical components. In FOOD case, similar products can be packed in different types of packaging, which affect the procurement of packaging materials.

In the INTIMATE_WEAR case, typical materials required for intimate products production are: fabrics (stretch-based fabrics which are mainly warp-knitted as opposed to weave-knitted), straps (made from elastics), hooks and eyes, elastics, embroideries, and packaging materials (display box and hanger). The majority of materials are unique for certain product ranges, styles, colours and sizes. A great deal of the differences in the material is driven by wide range of sizes (especially for bras) that the customer requires. For example, in order to produce 24 different sizes of bras, INTIMATE_WEAR requires 3-4 different hooks and eyes, 6 different sizes of straps, 4-8 different sizes of wires. This creates a big challenge for the company to respond to changes in the product mix. The challenges are illustrated in figure 4.7.

In the INTIMATE_WEAR case, the customer typically provides INTIMATE_WEAR with firm order and forecast of production. INTIMATE_WEAR uses the forecast to buy materials with long procurement time. Customers may change their forecast closer to the launch or selling season as they gain more information on the market trend.

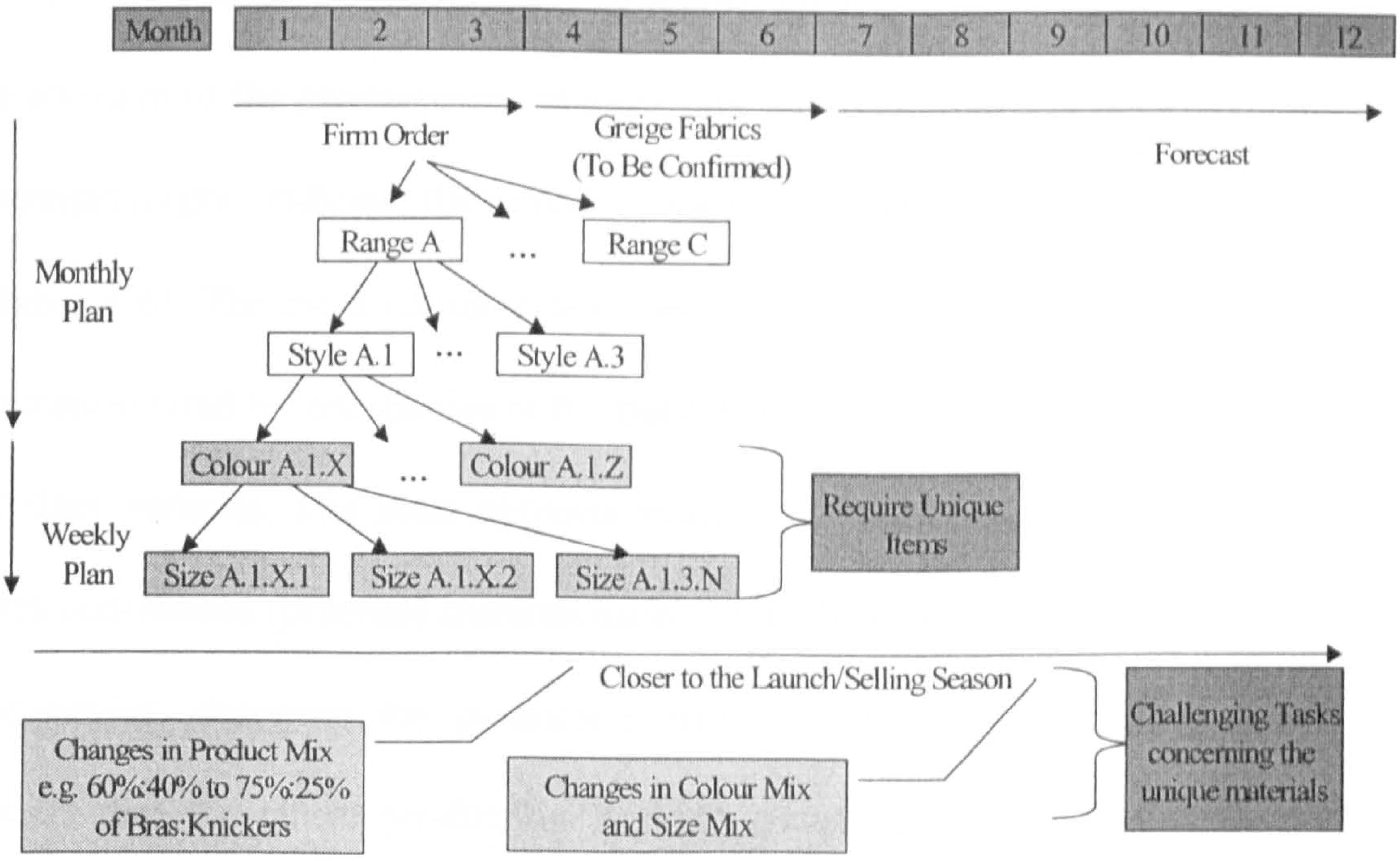


Figure 4.7 Difficulty to cope with changes in product mix

Most of INTIMATE_WEAR manufacturing units have the ability to handle all product lines and have multi-skilled workforce. Thus, the production is flexible enough to handle change in mix (proportion) to a greater or lesser degree than they anticipated. If there is a change in product mix between bras and briefs to 75:25% from the anticipated ratio of 60:40%, INTIMATE_WEAR production may be able to adapt to the change provided that they have the right materials. However, when the changes are associated with colour mix or size mix, then it would be difficult for INTIMATE_WEAR to handle these changes. As illustrated in figure 4.7, production of different colours and sizes of products require unique items specific to a product variant. Thus, INTIMATE_WEAR may not be able to accommodate changes in the colour mix and size at a short period prior to the selling seasons, or within seasons, as these materials may not be available at the right amount at the right time for production. This situation highlights the challenges associated with product variety that require specific materials.

4.3.7.4 The impact of product variety on production

In addition to the procurement of materials, findings from the empirical study, unsurprisingly, indicate that product variety affects the production process (Table 4.6). The most common and obvious impact of product variety on the operation cited by companies is the need for set-ups when producing different product variants. The most extreme evidence is found in the two companies with continuous (process) manufacturing, namely FOOD and SILICA. In both companies, changing the production from one type of product to another means that the entire production line has to be cleaned and re-setup. This process takes a considerably long time, which explains why both companies attempt to minimize changeover and product variety.

Other case companies indicate that variety driven by some factors have potentially greater impact on operations with respect to set up time, while some are less disruptive to the entire system. As shown in table 4.6, in the light bulb manufacturer's case, producing different light bulb diameters (small, medium, large, etc.) or changing from high to low voltage means that the production line needs to be re-setup entirely (taking around 8 hours), which has a relatively significant effect on production system utilisation. On the other hand, as long as the right materials (coil) are available, producing light bulbs with different wattage (25W, 50W, 200W, etc.) requires only minor set ups with only minimal disruption to the operations. In the three garment manufacturers, changes in the product style require longer change-over time because the workers need to be trained to cut and sew the new style.

On the contrary, producing different sizes or colours of product within the same style only requires minor set-up time.

4.3.8 Demand uncertainty

The framework proposes by Fisher (1997) is used to classify the product and identify the level of demand uncertainty facing each case company. Information obtained from the case companies in terms of demand uncertainty is used to add granularity to Fisher's framework. Figure 4.8 shows the relative level of demand uncertainty faced by the case companies.

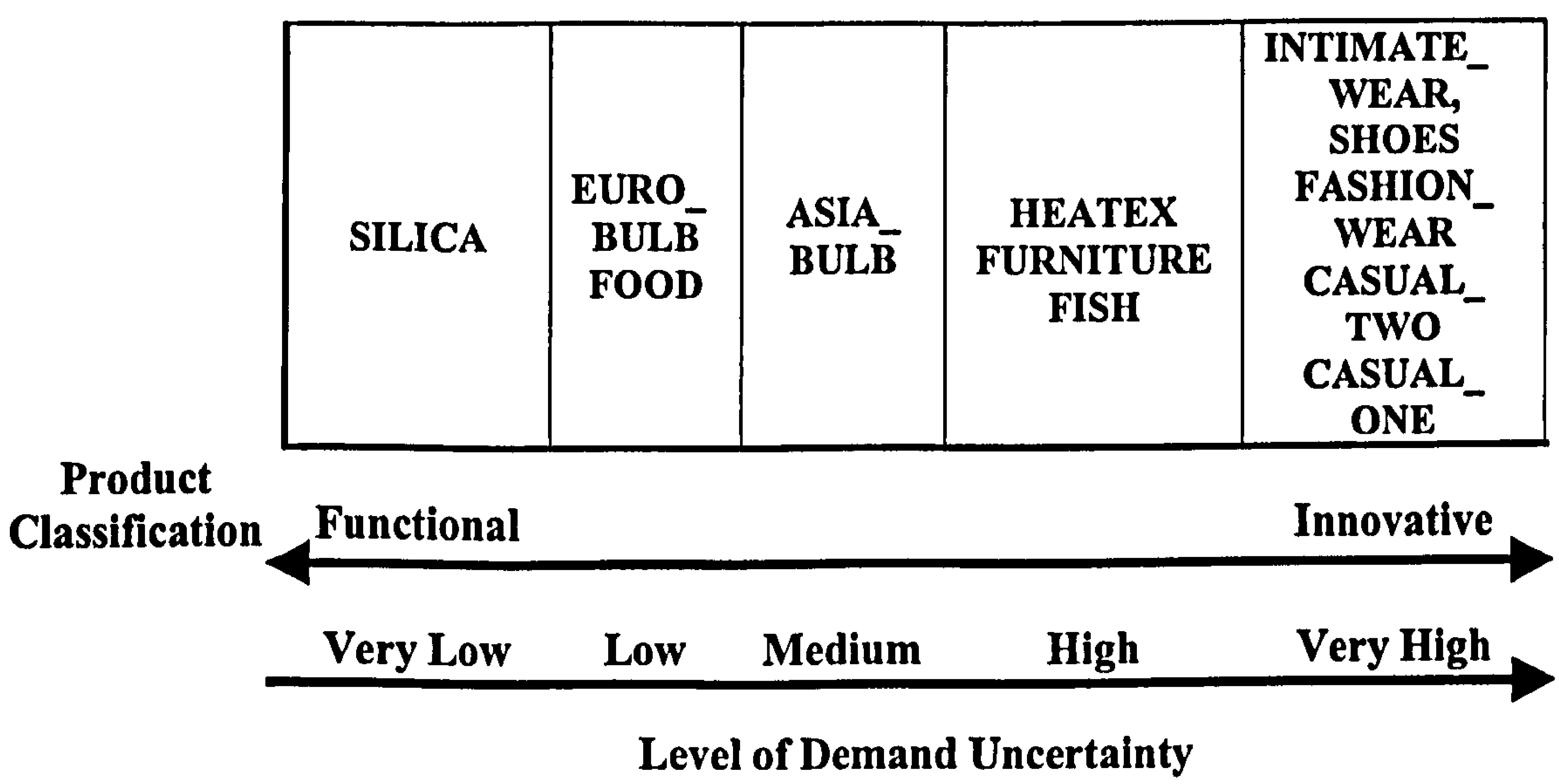


Figure 4.8 Level of demand uncertainty

The apparel products (shoes and various garments) can be classified as innovative products. The apparel product has high fashion content with short product life cycle. Thus, the five companies producing apparel products face high uncertainty in their demand. At the other end of the spectrum, chemicals produced by SILICA are fairly standard products. The variations in chemical products are very low, with a low rate of new product introduction. These products have long product life cycles, and their demand is relatively stable and predictable.

The demand uncertainty level for each of the rest of the companies is positioned somewhere between these two extremes. EURO_BULB and FOOD produce light bulbs and consumer food products, respectively, that can be classified as primarily functional products. However, both companies produce a wider variety of products and innovate their product more frequently in comparison to chemicals. Therefore, demand uncertainties facing these companies are relatively higher than SILICA. As discussed in the previous section, ASIA_BULB produces similar products to EURO_BULB. However, they innovate on the appearance of their product and offer more product variants to gain more market. This also means that they face higher uncertainty over their demand compared to EURO_BULB.

HEATEX and FURNITURE both produce innovative products according to customer order. The customer preferences change rapidly. As a result, both companies face highly unpredictable demand. Although FISH produces very standard product (processes shrimp), they only produce based on customer order. As they do not have long-term contract with the customer, their demand from one period to another is highly uncertain. They admit that they have peaks and troughs in their demand.

4.3.9 Supply uncertainty

The level of supply uncertainty facing each of the case companies are analysed based on Lee's (2002) framework. Lee (2002) suggested that some supply chains might face high supply uncertainty when the manufacturing process and the underlying technology are still under development and are rapidly changing. According to Lee's proposition, the manufacturing process and underlying technology in most cases in this study can be classified as mature. However, in SHOES, FISH and FURNITURE, supplies of raw materials are relatively unstable. FISH business relies on a supply of fresh fish that meets the required standard in size and quality. However, the availability of fresh fish is unpredictable depending on the farmer's yield at a certain time. Similarly, supplies of wood for FURNITURE or rawhides for SHOES are unpredictable depending on the supplier's yield.

In addition to Lee's proposition in terms of the stability of the supply base, supply uncertainty might also occur due to the distance between supplier and manufacturing facility (Levy, 1995; 1997). While most contract manufacturers buy from local suppliers with 2 – 6 weeks lead-time, MNC supply networks procure a great proportion of their materials from foreign suppliers (mainly Europe). According to the case companies, buying from foreign suppliers on average requires 8 – 13 weeks. Buying from foreign suppliers not only increases the average procurement lead-time, but also results in greater delivery uncertainty. As suggested by Levy (1995), "Distance not only increases shipping time but also the possibility of long delays caused by weather, strikes, or custom problems".

Based on the above analysis, the relative level of supply uncertainty facing each case company can be compared (Figure 4.9). The three garment manufacturers (FASHION_WEAR, CASUAL_TWO and CASUAL_CON) are faced with relatively low supply uncertainty as they have well-established local suppliers. FISH and FURNITURE face unpredictable materials availability. However, the overall supply uncertainty is lower as they procure mainly from local suppliers. Although ASIA_BULB, EURO_BULB, FOOD, SILICA and HEATEX generally have well-established supply bases, the fact that they are buying from global suppliers exposes them to supply delivery uncertainty. It is clear that SHOES faces the highest supply uncertainty because the supply base is still evolving and they buy primarily from foreign suppliers.

Characteristics of Supply Base	Local Supplier	Global Supplier
Evolving	FISH FURNITURE	SHOES
Stable	INTIMATE_WEAR (Contract manufacturer), FASHION_WEAR, CASUAL_TWO CASUAL_CON	INTIMATE_WEAR (Own facility), ASIA_BULB, EURO_BULB, FOOD, SILICA HEATEX

Uncertainty In Supply Delivery

Figure 4.9 Level of supply uncertainty

The long procurement lead-time forces most MNC supply networks to conduct procurement activities based on forecasts made far ahead of actual production. As discussed previously, most MNC supply networks work on a 'rolling forecast' consisting of production order and medium term forecast to plan their resources (capacity and material). Forecasts are updated every period to reflect the latest demand situation.

In the INTIMATE_WEAR case, the own manufacturing unit faces different levels of supply uncertainty compared to their contract manufacturers. Materials for production in INTIMATE_WEAR manufacturing facilities come from several countries such as Germany, Italy and Spain in addition to supply from UK suppliers. This means that the supply lead-time is subject to a level of uncertainty associated with transportation, customs or duties clearance. In contrast, INTIMATE_WEAR contract manufacturers produce their materials in-house or obtain the materials from local suppliers. Thus, INTIMATE_WEAR contract manufacturer face lower levels of supply uncertainty than their own manufacturing units.

4.3.10 The overall challenge in international supply chain management

The issue of product variety, supply uncertainty and demand uncertainty have been analysed separately in the previous three sections. However, more importantly, results from the empirical study indicate close relations between different factors in managing international supply networks: configuration, co-ordination, product variety, supply uncertainty and demand uncertainty.

The use of different types of materials is a common source of product variety found in most of the case companies. As a result, procurement of materials is affected by product variety. When a company produces more product requiring different types of materials, then the supply network configuration might be more complex as more suppliers are involved in the supply network. Requiring a wide variety of materials also means that more suppliers and more inventories need to be managed. This indicates that more product variety also adds complexity to the co-ordination of supply networks. As most MNC supply networks use foreign suppliers to supply materials for production facilities in Indonesia, the supply networks have to face greater levels of supply delivery uncertainty.

The level of product variety produced at a certain time or from one period to another also affects the predictability of demand. Randall and Ulrich (2001) suggest that product variety creates uncertainty in product demand. Results from the empirical study also indicate that companies producing high variety tend to have a higher level of demand uncertainty, particularly at the product level. It is also found that companies acting as contract manufacturers have relatively high demand uncertainty compared to subsidiaries of MNC corporations. This is unsurprising, as typically most contract manufacturers do not have long-term contracts with their customer. Thus, their demand pattern is characterised by peaks and troughs depending on the availability of orders from the customer.

Having understood the relations between these important factors, the overall challenge facing each case company is analysed. As the findings suggest that product variety relate closely to demand uncertainty, the product variety issues are captured in terms of demand uncertainty. Therefore, in alignment with

Lee's (2002) framework, the challenge facing each case company is analysed in two dimensions: demand uncertainty and supply uncertainty.

As indicated previously, more granularity is added in demand uncertainty dimension based on the information obtained from each case company. The overall challenge facing the supply networks is presented in figure 4.10.

Level of Supply Uncertainty	Very Low	Low	Medium	High	Very High
High					SHOES
Med	SILICA	EURO_BULB FOOD	ASIA_BULB	HEATEX FURNITURE FISH	INTIMATE_WEAR (Own facility)
Low					INTIMATE_WEAR (Contract Manufacturer), FASHION_WEAR, CASUAL_TWO, CASUAL_CON

Level of Demand Uncertainty

Figure 4.10 Demand and supply uncertainty

SILICA produces standard products with low variety, so demand uncertainty is very low. EURO_BULB and FOOD have a relatively higher level of demand uncertainty compared to SILICA as they offer a wider range of product variants. However, these three supply networks face medium level of supply uncertainty as they bought materials from foreign suppliers. In contrast, the three contract manufacturers producing garments are faced with high demand uncertainty as they offer highly seasonal products with short product life cycle. However, they have low supply uncertainty as they procure materials from local suppliers.

The rest of the cases face a combination of different levels of demand uncertainty and supply uncertainty. ASIA_BULB obtains a great amount of materials from European suppliers with average lead-times of 12 weeks. Although ASIA_BULB produces light bulbs that have a more standard demand compared to apparel products, ASIA_BULB has to order their materials 6 – 12 weeks in advance to ensure smooth running of the operations. Therefore, the company admitted that they have slow moving goods in their warehouse as they cannot adjust or amend orders for materials that have already been placed based on sales forecast made far ahead of the actual production. Similarly, HEATEX that manufactures heat exchangers according to customer order or specification and has to wait for materials procured by their head office. Problem occurs when the materials (components) are late or the customer needs to change the specification while the materials have already been ordered. FURNITURE and FISH face uncertainty in their demand and variability in material availability.

SHOES and INTIMATE_WEAR face the most challenging task in managing their supply network. Both companies produce high fashion, fast moving consumer goods. In this type of industry, getting products at the customer's shelf at the right time is crucial for the company. However, it is very difficult to predict which product variants (SKU) are going to sell. Several authors e.g. Fisher (1998) have proposed what is called 'Accurate Response' program suggesting that apparel supply chain should produce just small samples of product (SKU), launch them to the market and adjust production based on early market signals. In SHOES case, with such a long lead-time in their global pipeline it is difficult for the SHOES supply network to adjust their production once materials have been committed.

INTIMATE_WEAR operations are driven by the seasonal activities or selling seasons of the customer. INTIMATE_WEAR produces a wide variety of products. The majority of product variants produced by INTIMATE_WEAR require specific types of materials. Although both INTIMATE_WEAR and the customer attempt to anticipate the demand when they sign off the contract, typically there are always changes in the volume and mix of demand depending on how the market reacts to the products. If a certain product range is selling fast, customers may want the product before the due date and ask the company to bring the production forward. INTIMATE_WEAR production lead-time is about 5-8 weeks, so their pipeline may already have 4-5 weeks work in progress based on the previous demand. It is not easy to react and amend the production. It is also difficult for INTIMATE_WEAR if the changes in mix affect the procurement of materials, because they import some key materials from European suppliers, which have a certain degree of delivery uncertainty. For example, INTIMATE_WEAR will have difficulty to react to changes in the ratio of size of a certain product (bras), as it entails the procurement of size-specific parts. On the other hand, when a certain range of products are not selling well ('slow mover'), the customer might ask the company to slow the production or hold delivery of the products. This means that INTIMATE_WEAR has to bear the cost of storing the slow moving products in their warehouse.

The above discussion highlighted some of the most challenging problems in managing international supply network. One of the main orientations for the companies to develop its manufacturing unit in Indonesia appears to be the low labour cost that the country offers. However, without considering other factors such as the level of product variety that the manufacturing facility has to handle or the availability of capable supply base close to the manufacturing units, these advantages might be traded off by complexity in co-ordinating complex networks, customer cancellation due to late deliveries, costs that occur due to high inventory, express expedition of materials or late items etc. Thus, there is a need to demonstrate the potential impacts of, and inter-relations between, product variety, supply lead-time and demand uncertainty on supply chain performance.

4.4 Conclusions

The empirical study presented in this chapter has investigated twelve case companies involved in international supply networks with different types of ownership. Six of the case companies are subsidiaries of MNC's and five are contract manufacturers for foreign buyers. One company has a foreign manufacturing unit as well as using contract manufacturers to conduct some of its operations. The key findings from the empirical study are as follows:

- Results from the empirical study support propositions from the previous works in international operations literature indicating that configuration and co-ordination of MNC are influenced by product, industry and market characteristics.

- In addition to costs and market responsiveness as the commonly identified goal of international operations, many MNC supply networks attempt to achieve network flexibility and hedge the risks (demand swing, factory shut down, political problems etc.) by developing clusters of subsidiaries in the Asia Pacific region.
- MNC supply networks involved in the empirical study can be classified according to their configuration and co-ordination as: regional autonomous subsidiaries, regional clusters of subsidiaries and global supply networks.
- Considerable differences are evident in the nature of configuration and co-ordination of MNC's and contract manufacturer supply networks. Contract manufacturers produce less sophisticated product and are typically involved in mature and labour intensive industries.
- While the configuration of MNC's appears to be quite static over time, considerable co-ordination efforts are evident across elements in MNC supply networks. On the other hand, with no long-term commitment between elements in the contract manufacturer supply networks, the configuration dynamically changes and very little co-ordination is found between elements in the networks.
- Subsidiaries of Multinational Corporations typically use a global supply base to produce products for local, regional and global markets. On the contrary, contract manufacturers buy from local suppliers to serve foreign markets.
- An MNC, such as INTIMATE_WEAR, may combine the strategy of owning manufacturing facilities and subcontracting to a third party. INTIMATE_WEAR ensures certainty and reliability of their production by

keeping some of their production in-house. Keeping some of their operations close to the customer also enables them to be more responsive to changes in the market. At the same time, they achieve significant cost, scale and scope advantages while sharing some of the risks in demand uncertainty by engaging with the contract manufacturer located in relatively low-cost region.

- Most of the MNC supply networks involved in the empirical study bought materials for production in their manufacturing units in Indonesia from European (global) suppliers. This policy subjects the supply networks to typically long and uncertain supply delivery.
- Companies producing different products have different factors that generate product variety.
- The level of simultaneous and sequential variety varies across different case companies even within the same industrial sectors. One of the companies producing light bulbs introduces additional factors to their product that create higher product variety compared to its competitor. Most companies in a make-to-order environment have higher levels of sequential variety relative to simultaneous variety. The level of product variety influences the companies' ability to forecast their demand.
- Product variety generally affects the procurement of materials. In some cases, variation in material is the main source of product variety. In other situations, the factors generating product variety indirectly affect the procurement activities.
- The case companies also confirm that their operations are affected due to the need to set up facilities when producing different types of product. In

continuous manufacturing, product variety is associated with long changeover times. In some cases, certain attributes have a greater impact on operations compared to other attributes.

- Analysis from the empirical study indicates that the challenges facing international supply networks producing high variety need to be investigated further.
- There is a need to investigate, further understand and quantify the potential impacts of different configuration and co-ordination as well as different factors such as product variety, and demand and supply uncertainty on supply chain performance. Modelling and quantifying the potential impacts of the above factors on the supply chain performance is expected to show the potential for improvement and enable the development and proposition of strategies to address the problems.

Chapter 5
Model Development

5.1 Introduction

The analysis in chapter 4 showed that companies involved in real international supply networks apply different configuration and co-ordination strategies. Most real international supply chains involved in the empirical study face problems associated with product variety. At the same time, the companies also have to cope with supply uncertainty and demand uncertainty in managing their international supply networks. Whilst the empirical study provides important insights on the factors that need to be considered in managing product variety in international supply network, it provides only limited understanding on how these factors i.e. configuration, co-ordination, product variety, demand uncertainty and supply uncertainty affect the performance of international supply networks.

Further study is required to investigate: 1) the inter-relations among different factors identified in the empirical study and 2) the magnitude of impact caused by different factors on the performance of international supply networks. Another purpose of the simulation study is to be able to provide insights on potential strategies to mitigate the negative impacts of these factors. A simulation study is determined as the best method to achieve these objectives. The development of a simulation model based on the insights from the empirical study is described in this chapter.

The chapter begins with the identification of cases that are relevant to the model development in section 5.2. Section 5.3 describes: 1) a general overview of the simulation environment, 2) the configuration and co-ordination aspects captured in the simulation environment, and 3) the terminology used and 4) assumptions used throughout the simulation study. An overview of the simulation experiment is presented in section 5.4. This is followed by descriptions of the factors and performance measures captured in the simulation model provided in section 5.5 and 5.6, respectively. The simulation application is explained in section 5.7. Section 5.8 describes the setting of the reference input data and experimental factors. Verification and validation of the simulation model is described in section 5.9. Finally, tactical planning for the simulation experiment is described in section 5.10.

5.2 Identifying relevant cases

To investigate the problems of product variety in the context of international supply networks, we aim to develop a simulation model that has 'generic' features of an international supply networks and that provides a good representation of the problems associated with product variety. However, results from the empirical study provide a wide spectrum of findings in relation to products and processes, as well as different configuration and co-ordination characteristics. Thus, the first step is to identify cases that provide relevant and similar characteristics to develop a 'generic' model.

As discussed in chapter 4, results from the empirical study found differences in the configuration aspects across the case companies. Major differences are found between companies belonging to Multinational Corporation (MNC) supply chains and those of contract manufacturer's supply chain. There are two main reasons that lead us to focus on developing the model that captures the characteristics of MNC supply networks:

1. The MNC supply networks tend to have a more 'static' structure over a relatively long period, while the supply networks of contract manufacturers tend to change dynamically as the elements involved in the supply network change from one period to another.
2. More co-ordination efforts are found in MNC compared to contract manufacturer's supply networks. Most contract manufacturers involved in the empirical study still work in transactional buyer-supplier relationships with minimal co-ordination efforts or information sharing.

The product variety problems faced by different companies depend on the companies' product and manufacturing process characteristics. FOOD and SILICA have primarily continuous production lines, while the rest of the cases have mainly discrete manufacturing processes. In FOOD and SILICA supply networks, product variants are mainly differentiated by different chemical contents. These will be difficult to capture in the model. HEATEX supply chain is also an extreme case, as it is the only company involved in the empirical study, which produces unique products customised to customer orders in a job shop production environment. HEATEX can produce a wide variety of products with relatively small volume of production for each product variant. These 'extreme' cases will not be the focus in developing the simulation model.

Having identified the extreme cases, four cases, namely SHOES, INTIMATE_WEAR, ASIA_BULB and EURO_BULB appear to be most relevant in developing the simulation model. The four cases have similar characteristics that are captured and investigated in the simulation environment, as follows:

- Product: the four companies produce different types of consumer products that are not technologically complex.
- Manufacturing process: the manufacturing can be classified as primarily discrete processing. As presented in table 5.1, in general, the manufacturing processes in the four cases can be classified into three sequential stages of production. The first stage of production is associated with the main material preparation that usually involves fabrication or manufacturing operations of raw (main) materials followed by assembly processes. The final stage in the production process consists of finishing and packaging of finished products. In addition, manufacturing of products can be done in several batches.
- Configuration: The supply networks belong to MNC. As discussed in section 4.4.1.2, the major elements involved in the four MNC supply networks include suppliers, manufacturer, sales office, wholesalers and corporate headquarters. Sales offices, wholesalers or distributor and in some cases corporate headquarters are in charge of demand management activities. These elements are referred to as "internal customers" because

they transform demand information from the end customers into production demand for the manufacturer. The configuration of these supply networks tend to remain fixed over a relatively long period of time.

- Co-ordination: The production is triggered by production demand from internal customer.
- Product variety: Variation in product is influenced, to a different extent, by the use of different types of materials at different stages of the production process.

Table 5.1 Production stages of four case companies used as bases for simulation model

Case	Process 1 - Main Material Preparation	Process 2 - Assembly Process	Process 3 - Packaging
SHOES	Converting rawhides into finished or semi-finished leather, cutting the leather into shoe uppers	Stitching shoe uppers, putting accessories	Packaging
INTIMATE_WEAR	Fabrics preparation, cutting fabrics into different style	Sewing, putting accessories (lace, sequins, buttons)	Finishing and packaging
ASIA_BULB & EURO_BULB	Glass furnace, bulb blowing, capsule production and PCB work	Assembling different parts	Packaging

5.3 Simulation environment

5.3.1 Overview

Insights from the four cases identified previously are used as a basis in developing the simulation model. Information regarding the configuration aspects gained from the case companies are used as a platform to develop the structure of the simulation model, while the knowledge on co-ordination provides the 'logic' for the information and material flow in the supply chain. Several important problems facing the case companies highlighted in chapter 4 including demand uncertainty both at the aggregate-level and product-level, supply lead-time uncertainty and product variety are treated as factors to be investigated using the simulation model. Before giving the overview of the simulation environment, several important terms used throughout the simulation study are summarised in table 5.2.

Table 5.2 Summary of terms in the simulation analysis

Terminologies	Explanations
Demand	The amount of products ordered by internal customers to manufacturer
Aggregate-level demand	The total amount of products ordered by internal customers to manufacturer
Product-level demand	The amount of order for a certain product variant requested by internal customer
Product variety	The number of different product variants produced in the system over a certain period of time
Product variant xyz	Product variant requiring packaging material x, main material y, and unique material z
Sources of variety	Main material, unique material and packaging material
Main material	Representing raw material required in process 1, which is available in various options
Unique material	Representing auxiliary material, part or sub-assemblies, etc required in process 2, which is available in various options
Packaging material	Representing finishing or packaging materials required in process 3, which is available in various options
Material option	Specific type of material
Process batch	The quantity of items processed in one production run
Transfer batch	The quantity of items transferred from one process to the next
Supply lead-time	The length of time from when the manufacturer places an order for material until it is received
Local supplier	Supplier located in the same country as the manufacturer
Global supplier	Supplier located in different country as the manufacturer

The simulation environment is presented in figure 5.1. It is developed to incorporate the characteristics of the four case companies. The simulation environment represents a three-stage Multinational Corporation supply network consisting of 1) suppliers, 2) a manufacturer and 3) internal customers.

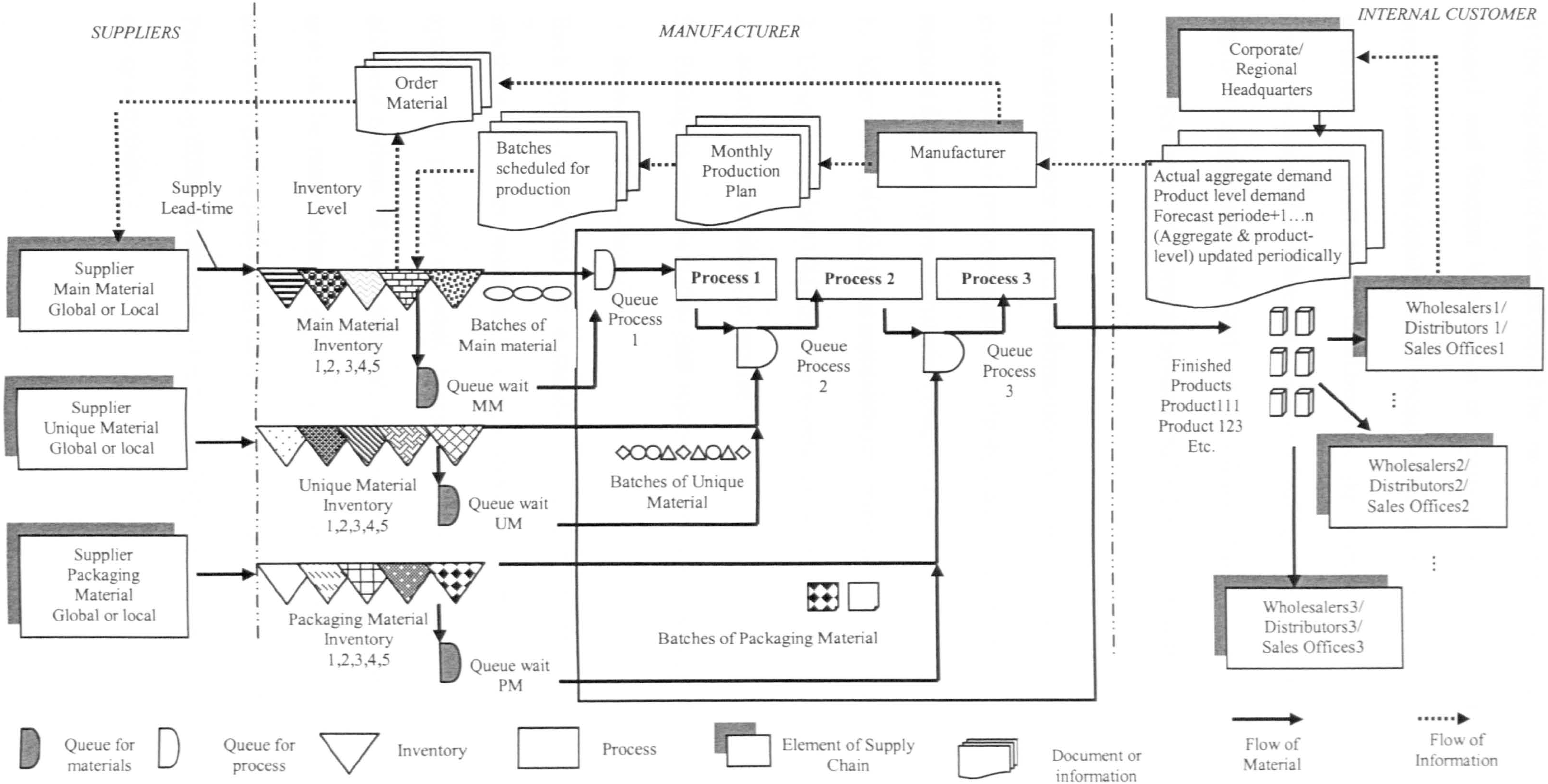


Figure 5.1 Simulation environment

At the beginning of a certain period the internal customers generate production demand and forecast information at aggregate and product level for the manufacturer. The demand and forecast information are updated every period to reflect the most recent conditions in the marketplace. This continuous update on demand and forecast is called a "rolling forecast system". This also captures *aggregate-level* and *product-level demand uncertainty*. More information on rolling forecast system can be found in **appendix 2.**

The manufacturer uses the information from internal customers to plan its production and procure materials. Production of a certain product variant requires different types of materials classified as:

1. Main material (MM) that represents raw material fabricated in process 1
2. Unique material (UM) that represents an auxiliary material, parts or sub-assemblies, assembled in process 2.
3. Packaging material (PM) that represents packaging and general finishing items used in process 3.

Each type of material has a number of options represented by different numbers e.g. main material 1, unique material 2, etc. The manufacturing system can produce different types of product through combination of different options of main material, unique material and packaging material used in the manufacturing processes. For example, product variant 123 is a product requiring packaging material 1, main material 2 and unique material 3. Processing different materials at different stages of manufacturing will require set-up activities.

Each type of material can be obtained from a *local supplier* located in the same country or a *global supplier* located in different country. The length of time required by a supplier to deliver the material is subject to uncertainty referred to as *supply lead-time uncertainty*. Due to the additional transportation time, buying materials from global supplier requires a relatively longer lead-time compared to buying from local suppliers. Thus, the manufacturer has to place orders further ahead of production if the materials are bought from global suppliers. Different types of material received from suppliers are stored in different inventory storages as shown in figure 5.1.

The manufacturer conducts production based on the internal customer orders. The production of a certain product variant is divided into several *batches*. The method of dividing product-level demand into batches is described in section 5.7.3. Sequencing the production of batches is determined using a certain scheduling rule that will be described in section 5.7.4. Before production schedule is executed, the availability of materials to produce each batch is checked. If materials required for a certain batch are not available in the right amount, the materials are not assigned to the batch. If materials are available, they are assigned for a specific batch and sent to the queue for respective processes.

Figure 5.1 shows that the full manufacturing process is divided into three stages namely process 1, process 2, and process 3 to reflect the manufacturing processes of the four case companies on which the simulation is based. In each stage of the process, there is a queue to enter the process. As soon as process 1 is available, main materials are processed in process 1. Output of process 1 is assembled with unique materials in process 2. As process 2 is completed, output of process 2 is packed and finished with packaging materials in process 3. In each stage of the process, the batch is delayed if the correct materials are not available for that batch. Delayed batches wait in the corresponding queue for materials (e.g. queue wait MM) until sufficient materials are available. Processing different option of materials in each stage of production will introduce a certain period of delay due to set-up activities. The entire stages of production are assumed to be conducted at the same plant and there is no time associated with transferring batches of production between processes. Finally, finished products are assigned to satisfy the internal customers demand.

Based on the above explanation, configuration aspects captured in this model are: 1) major elements involved in the international supply chain and 2) geographical separation between key elements. One important aspect of an international supply chain configuration captured in the model is the geographical separation between manufacturer and supplier. The geographical separation between manufacturer and supplier determines the lead-time between placement of an order until the manufacturer receives the material i.e. supplier delivery time factor.

The co-ordination among elements in the international supply chain is reflected in the flow of information and flow of material in the simulation environment. The information flow captured in the model includes:

1. Monthly demand and forecast information from internal customer to manufacturer.
2. Purchase order from manufacturer to supplier.

5.3.2 Assumptions in the simulation study

In developing the simulation model, several assumptions are applied:

1. The system works in an operational month consisting of 20 working days. The capacity per month is assumed to be constant.
2. There is very little literature on how to generate product-level demand and incorporate uncertainty in the product level. Product-level demand is generated here as a proportion of aggregate-level demand. The method will be described in section 5.7.2.
3. No planned level of safety stock of materials and finished goods is assumed. The assumption is made in order to avoid adding complexity at this initial work but is an aspect highlighted for further work.
4. The entire production processes are conducted in the same plant.
5. In the production system, a scheduling rule that minimises the set-up time occurring in production and ultimately minimises the average lead-time is applied.
6. Each type of material as a determinant of product variety can have 1, 3 or 5 different options representing low, medium and high levels of variety. These numbers of options provides enough flexibility to investigate the level of variety (up to 125 different products) without making the models too complex. This assumption leads to 125 number of product variants in the maximum variety situation.

7. Set-up time, which occurs when different material options are processed subsequently in a certain process, is assumed to be constant for all processes and sequence independent.

5.4 Overview of simulation experiment

The simulation model described in the previous section is used to investigate different conditions facing international supply chains in terms of product variety, demand uncertainty and supply uncertainty. First, experiments investigating the situation when the system produces different levels of product variety whilst demand and supply remains constant are conducted. Results from this set of experiment will be used as a point of comparison in analysing the results of other sets of experiments i.e. reference case. The next set of experiments investigates the situation when the system produces different levels of product variety whilst supply lead-time is uncertain, but demand is constant. The next set of simulation experiments investigate the condition when the system produces different levels of product variety, whilst aggregate-level and product-level demand is uncertain, but suppliers deliver with constant lead-time. The final set of the simulation experiments investigate the situation when the system produces different levels of product variety and both demand and supply are subject to uncertainty.

5.5 Simulation factors

There are three main factors to be investigated in the simulation including product variety, supply lead-time uncertainty, and demand uncertainty.

5.5.1 Product variety

The supply network produces different levels of product variety in response to demand. In the model, the level of product variety offered by the system is determined by: 1) the number of options for main material, unique material and packaging material and 2) combinations of different main material, unique material and packaging material.

5.5.2 Supply lead-time

The second factor investigated in this model is supply lead-time, which is determined by the location and the reliability of suppliers. Location of suppliers is expected to influence the length of the supply lead-time due to differences in response and transportation time. Suppliers located in the same country as the manufacturer (*local supplier*) are expected to deliver faster compared to suppliers located in a different country (*global suppliers*).

In addition to location of suppliers, supply lead-time is also determined by the reliability of the supplier. Ideally, the supplier delivers just in time. However, in reality, suppliers usually deliver earlier or later than the expected lead-time. The range of supply lead-time is expected to be smaller if the supplier is local. When the manufacturer buys from a global supplier, the supply lead-time not only constitutes transportation times, but also the possibility of long delays raised by some problems associated with production, transportation or customs or unexpected problems due to weather, strikes, etc. As a result, delivery uncertainty in buying from global suppliers is greater, which needs to be reflected in a greater range in the global suppliers' lead-time. Further explanation in specifying the parameters for distribution of supply lead-time will be provided in section 5.8.2.1.

5.5.3 Demand uncertainty

The last factor to be investigated in this study is demand uncertainty, which can take the form of aggregate-level demand uncertainty (volume) and product-level demand uncertainty (mix). The literature (Fisher, 1994; Randall and Ulrich, 2001) and results from the empirical study suggest that demand uncertainty is closely related to the level of product variety. The international supply chain producing higher levels of product variety is typically faced with higher demand uncertainty particularly in the form of product mix uncertainty.

In order to capture the key aspects of both volume and product mix uncertainty, demand is generated at two levels: aggregate-level demand and product-level demand.

1. Aggregate-level demand represents the volume of product required within a certain month without differentiating it into product variants. A typical shape of aggregate demand that we will generate in the model is shown in figure 5.2. This figure shows a demand pattern with long-term average of 16,875 and standard deviation of 3,375. The level of uncertainty measured by coefficient of variation (CV) is 20%. Volume uncertainty is reflected in the random deviation of demand from its average value. The mechanism to generate demand uncertainty will be discussed in section 5.7.1.

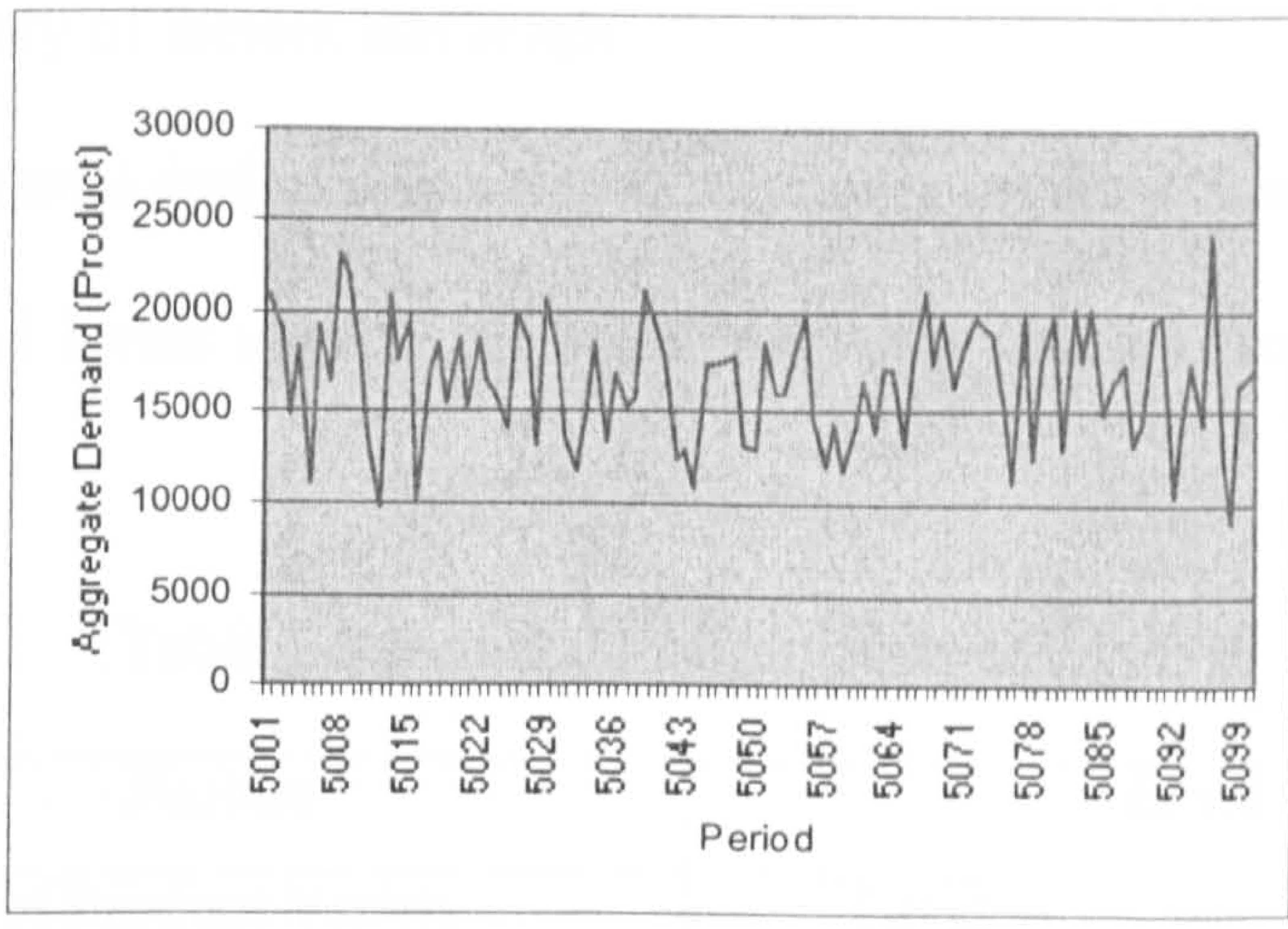


Figure 5.2. Aggregate demand pattern

2. Product-level demand represents the volume of a specific product variant required in a certain month. Product-level demand constitutes the product mix that the manufacturer has to produce in a certain month. Product mix represents the 'composition' of product variants e.g. if in month one the system has five options of main material then the aggregate-level demand of 16,875 units might be divided into 40% of product 111, 25% of product 121, 20% of product 131, 10% of product 141 and 5% of product 151 (Figure 5.3). In the following month, this composition may remain constant or may change as illustrated in figure 5.3. Changes in the composition of product-level demand from one period to another represent the product mix uncertainty in the supply system.

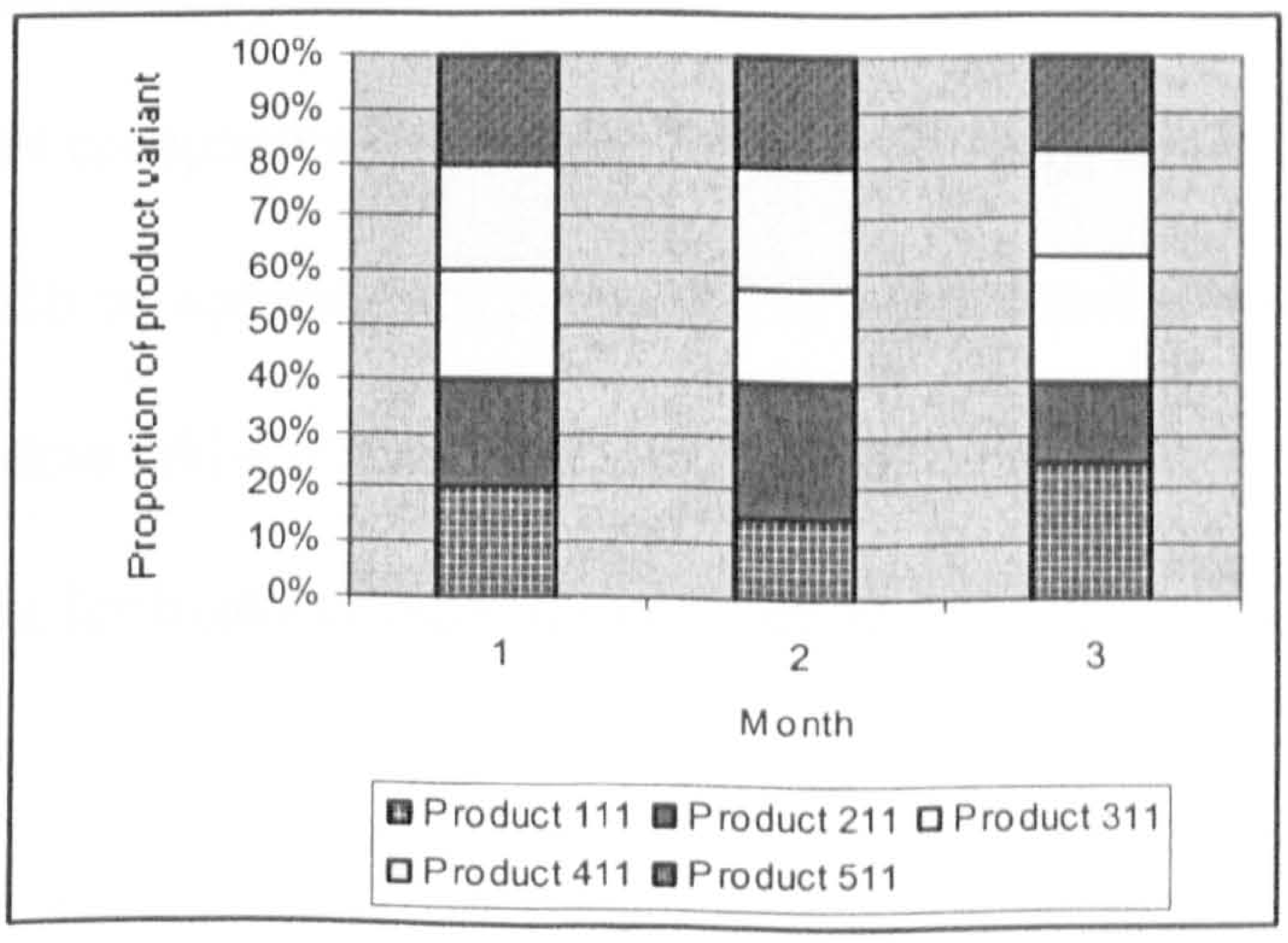


Figure 5.3. Example of product mix changes

5.5.4 Summary of factors and levels

Using experimental design principle each factor is tested at a number of levels. The factors and levels used in the simulation experiments are summarised in table 5.3.

Table 5.3 Summary of factors and levels

No	Factors	Level	
	Sources of Product Variety	**Level 1**	**Level 2**
1	No. of different main materials	1	5
2	No. of different unique materials	1	5
3	No. of different packaging materials	1	5
	Supply Lead-time	**Level 1**	**Level 2**
4	Main material supply lead-time	Local	Global
5	Unique material supply lead-time	Local	Global
6	Packaging material supply lead-time	Local	Global
	Demand Uncertainty	**Level 1**	**Level 2**
7	Aggregate-level demand	Constant	Variable
8	Product-level demand	Constant	Variable

5.6 Performance measures

In this model we are particularly interested in investigating the impact of product variety on the amount of time that a product spends in the system i.e. flow time and level of inventory. The study measures average flow time and average level of inventory. The decision to choose these two performance measures is motivated by:

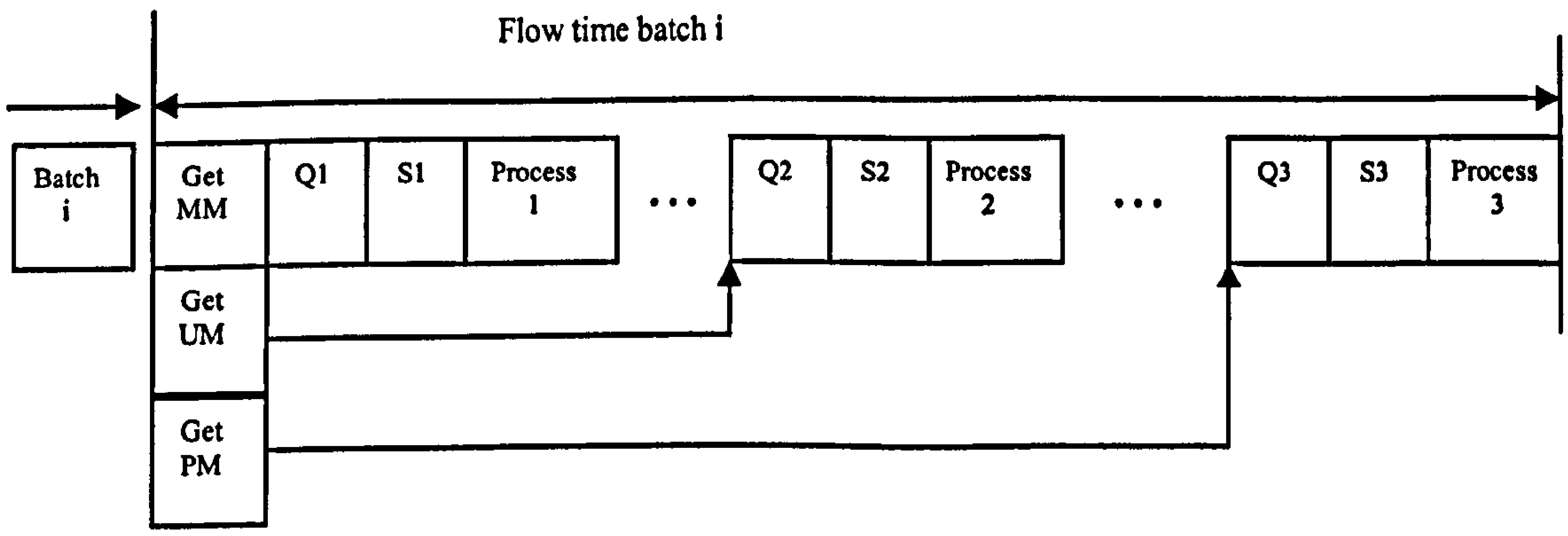
1. The fact that companies, especially those producing fast moving consumer products such as apparel, are pressured to offer a wide variety of products in a short time (Al-Zubaidi & Tyler, 2004). Lead-time is certainly a key performance for many companies competing in today's environment.

2. If different product variants require different types of materials, then the level of inventory is directly associated with the level of product variety. Thus, the impact of product variety on inventory needs to be captured.

The average flow time is influenced by tardiness of material delivery and delays in production. Therefore, measures of material tardiness and delay in production are also collected to enable verification of results and support the analysis.

5.6.1 Measures of flow time

Flow time is measured as the period of time a product spends in the system from the time actual demand of the product is generated by internal customer until the product is completed. As the production of any product variant is done in batches, the flow time for each batch is measured. Figure 5.4 illustrates the determinants of flow time of a specific batch.



Get MM	- Waiting time to get main material
Q1	- Queue time to utilise process 1
S1	- Set-up time in process 1
Process 1	- Processing time in Process 1
Get UM	- Waiting time to get unique material
Q2	- Queue time to utilise process 2
S2	- Set-up time in process 2
Process 2	- Processing time in Process 2
Get PM	- Waiting time to get packaging material
Q3	- Queue time to utilise process 3
S3	- Set-up time in process 2
Process 3	- Processing time in Process 2

Figure 5.4 Calculation of flow time in the simulation model

Flow time of a batch is determined by four main factors including:

1. *Time to get the right material for production* (Get MM, Get UM and Get PM). If materials arrive on the expected date so that they are available in stock when required for production, the time to get materials from stock is zero. On the other hand, a waiting time to get a certain type of material will occur when material delivery is late.
2. *Queue time in each stage of processing* represented in figure 5.4 as Q1, Q2 and Q3. As described previously, the production of a certain product variant is divided into several batches (section 5.7.3). Scheduling of the batches is described in section 5.7.4. Queue time for a certain batch is affected by several factors including the batch size and level of product variety. The larger the batch size, the longer the time is spent in the queue to utilise a certain facility. In addition, when the system produces more than one type of product variant, the queue time of a certain batch depends on the schedule for production.
3. *Set-up time* in each stage of processing (S1, S2 and S3 in figure 5.4). Set-up time will occur when different material options are produced sequentially in a specific process.
4. *Processing time* is the amount of time required to conduct each stage of the process.

Once the flow time for all the batches in a simulated period are measured, the average flow time per product throughout the simulation is calculated as follows:

$$\text{Average flow time per product} = \frac{\Sigma(\text{Flow time of batch}_i \times \text{Volume of product in batch}_i)}{\Sigma\,\text{Volume of product in batch}_i} \qquad (5.1)$$

5.6.2 Measures of inventory

In this model we will also measure the level of inventory held in the system both for specific types of material (main material, unique material and packaging material) as well as the total inventory referred to here as 'system inventory'.

$$\text{Average of individual material inventory} = \frac{\text{Level of inventory x Period of time inventory at this level}}{\text{Total elapsed simulation time}} \quad (5.2)$$

$$\text{Average system inventory} = \text{Sum (Average of individual material inventories)} \quad (5.3)$$

5.6.3 Measures of Material Tardiness

Supply lead-time uncertainty is one of the main factors investigated in the simulation study. An average (expected) supply lead-time for local and global supplier is set. Supply lead-time uncertainty results in materials arrive earlier or later than the expected arrival time or due date. If material arrives later than the due date then the production will be delayed. In order to capture the impact of such occasions, an intermediary measure of material tardiness is captured in the simulation study.

When a specific material arrives later than the expected lead-time, the material tardiness is calculated **according to formulae proposed by Hopp and Spearman (2000, p. 489)**:

$$\text{Material tardiness} = \text{Arrival time} - \text{expected arrival time} \quad (5.4)$$

Otherwise, material tardiness is zero.

5.6.4 Delay time in production process

Measures of delay are another intermediary measure captured in this model. Delay of production of a certain batch in this model is primarily caused by material shortages due to lateness in material delivery or if material available in stock is less than the production requirement. Thus measures of delay are related to measures of tardiness. However, delays can also occur due to queuing and set-ups. Therefore intermediate measures are needed to capture not only delays due to material lateness but also other types of inefficiencies such as queuing and set-up expected to occur in high variety and highly uncertain situations. If the production of a certain batch runs without any delay, process 2 will start as soon as process 1 is finished and process 3 will start immediately after process 2 is finished.

$$\textit{Delay of batch}_n \textit{ in process 1} = \textit{Time process 1 starts} - \textit{Time production is scheduled to begin} \quad (5.5)$$

$$\textit{Delay of batch}_n \textit{ in process 2} = \textit{Time process 2 starts} - \textit{Time process 1 is completed} \quad (5.6)$$

$$\textit{Delay of batch}_n \textit{ in process 3} = \textit{Time process 3 starts} - \textit{Time process 2 is completed} \quad (5.7)$$

5.7 Developing and implementing the simulation environment

The simulation environment described in the previous section is developed using General Purpose System Simulator (GPSS) World^{TM}. One of the main appeals of GPSS is that it offers great flexibility to the modeller to "write" their own logic and to incorporate complex logic. GPSS is designed to be simple enough to use by engineers who are not expert computer programmers (Pidd, 1998, p.145). This goal appears to be sensible as it is still in use 30 years after its appearance on the market although the software is much improved. The creator also argued that "GPSS is designed to deliver answers quickly, without requiring unnecessary preparation of elaborate visualizations" (Minuteman Software).

The simulation model uses a discrete event system with daily time units. The general logic of the simulation application is shown in figure 5.5. Overall, the simulation application comprises six main modules as follow:

1. Aggregate-level demand and forecast generation. The first module generates aggregate-level demand and forecast(s) at the beginning of a simulated month. As shown in the top part of figure 5.5, there are two different procedures to generate aggregate-level demand depending on the setting of simulation experiments. The first procedure is used to generate demand for experiments with constant demand. In experiments with uncertain aggregate-level demand, the second procedure is used to generate aggregate-level demand that varies from one period to the next. This module is described in more detail in section 5.7.1.
2. Product-level demand and forecast generation. The second module transforms the aggregate-level demand and forecast generated in the first module into product-level demand. The module consists of generating proportions for each type of material (packaging, main and unique materials) that constitute a specific product variant over the aggregate demand. There are also two different procedures to generate product-level demand. The first procedure in this module is used to generate constant product-level demand, while the second procedure generates variable product-level demand for experiments with uncertain product-level demand. This module is discussed in section 5.7.2.

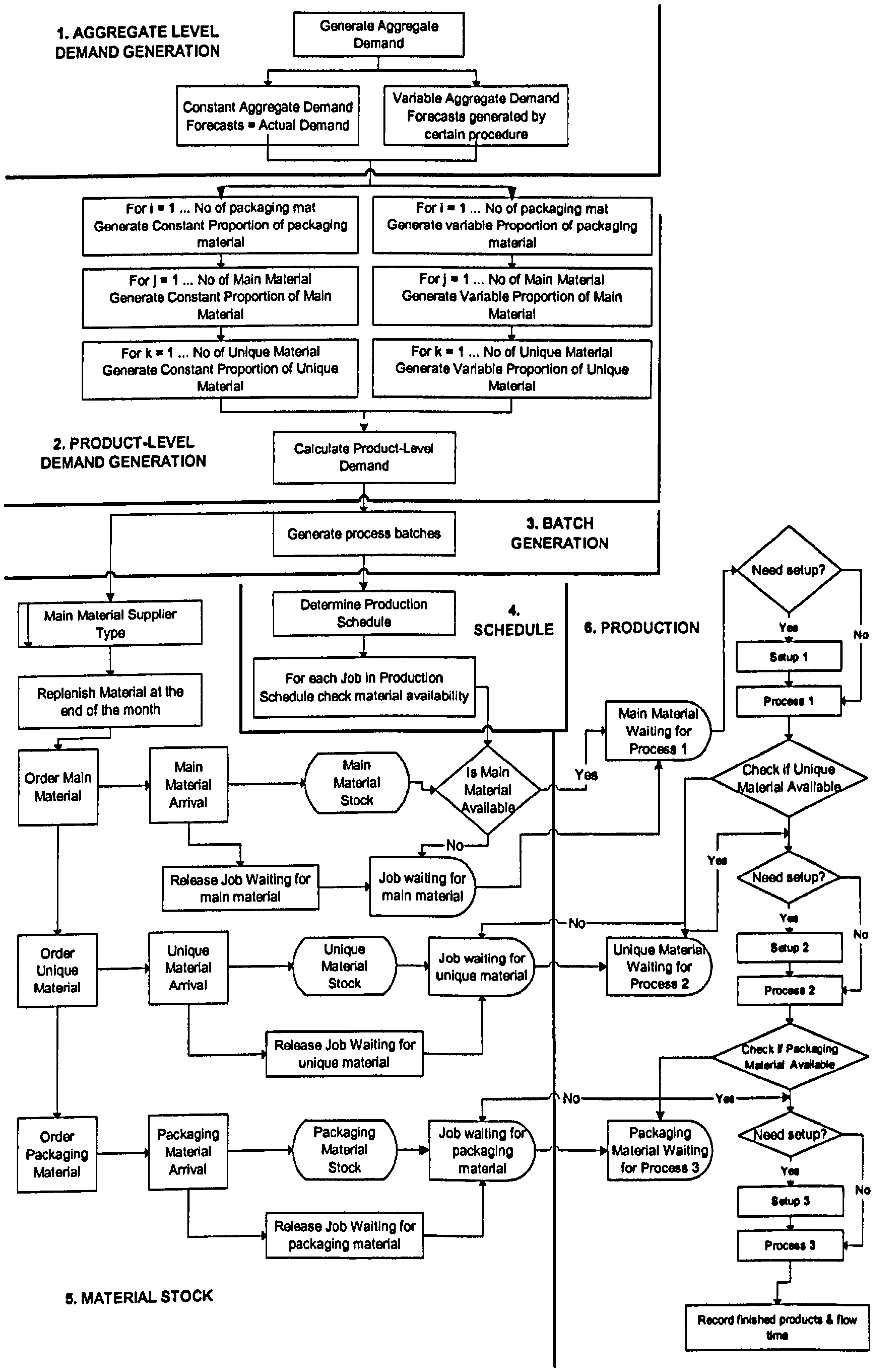


Figure 5.5. Logic of simulation model

3. Batch generation. In the third module demand for each product variant is divided into several batches (section 5.7.3).
4. Production schedule. When the entire product-level demand has been divided into process batches, a schedule for production is generated in the fourth module. The scheduling rule will be described in more detailed in section 5.7.4.
5. Material stocks. This module (located in the bottom left part of figure 5.5) controls the movement of materials. Each type of material option is stored in individual storage and is managed independently. The module receives input from production schedule that triggers the process to assign material to a certain process batches. Materials assigned for a scheduled batch is removed from the stock to the respective process queue. The module interacts closely with production module as it holds batches that are delayed due to material shortages. When materials are received from the suppliers, delayed batches are released to join the process queue. The module also receives information regarding future materials requirement from the first and second module. At the end of the month, the stock is replenished based on the future requirements, material available in stock and in transit. More detailed description on this module is presented in section 5.7.5.
6. Production. In the sixth module (bottom right part of figure 5.5), production of batches is conducted. The module controls the queue for each stage of the process. It also checks if the material required by a certain batch is available in the queue of each process. If material is not available the batch is placed in queue waiting for materials (material stock

module). When material is available, the module checks whether set-up is needed in each stage of the process and carries out the production process. Section 5.7.6 descriptions this module in more detail.

5.7.1 Aggregate-level demand and forecast generation

At the beginning of each simulated operational month, the aggregate-level demand is generated. As mentioned in the previous section, there are two procedures for generating aggregate-level demand depending on the patterns required.

5.7.1.1 Constant aggregate-level demand (constant volume)

In the first procedure, the aggregate demand each month is given a deterministic value that remains constant over the simulation period. The forecasts for a certain period ahead are assumed to be equal to the actual demand.

5.7.1.2 Variable aggregate-level demand (uncertain volume)

The second mechanism is designed to generate variable aggregate-level demand that randomly changes from one period to another. The general assumption is that the average long-term demand is known. However, the actual monthly demand varies from the average value, creating uncertainty in the aggregate-level demand. The uncertainty in aggregate-level demand and forecasts are generated by the following formulae:

$$F(i, j) = x + a\, d(i) \quad (5.8)$$

$$d(i) = F(i-1,i) + e(i) \quad (5.9)$$

Where:

F(i, j) = forecast made in period i for period j

x is minimum forecast (volume)

a is a constant ($0 < a < 1$)

d(i) is actual demand in period i

e(i) is forecast error in period i that is assumed to be normally distributed with mean zero and standard deviation *ForError* i.e. N(0,*ForError*)

In this procedure, the actual demand in any period is determined by the forecast made in the previous period plus a random error that is normally distributed with mean zero. The specified standard deviation of the forecast error (*ForError*) controls the level of uncertainty in the aggregate-level demand. The process to set a value for *ForError* is described in section 5.8.2.2. As shown in equation 5.8, the value of the forecast for each forecast period is determined by the actual demand in that period, d(i), times a constant value (a) plus a minimum amount of forecast (x). The minimum amount of forecast is introduced to ensure that the demand will not have extreme values e.g. a zero demand level.

Results from the case companies indicate that forecasts predicting further into the future have higher uncertainty and possibility of errors. To incorporate this into the forecast generation procedure, the minimum amount (x) decreases as the forecast predicts further into the future. Thus, for forecast 4 months ahead:

Minimum amount for forecast i+1> minimum amount for forecast i+2>minimum amount for forecast i+3 > minimum amount for forecast i+4

The length of the forecast horizon depends on the supplier's lead-time. When suppliers are assumed to have a 3 month lead-time, then material for production in month 4 has to be bought in month one. This means that in month one, forecast of demand in month 4 has to be available. If materials are bought from a supplier that can deliver in one month they only need to be bought based on the forecast made one month in advance.

5.7.2 Product-level demand and forecast generation

Aggregate-level of demand and forecasts are broken down into product-level demand. As suggested previously, a product variant is given a code based on the use of main material, unique material and packaging material. Product 111, for example, represents a product requiring packaging material 1, main material 1 and unique material 1, while product 342 represents a product that requires packaging material 3, main material 4 and unique material 2.

In order to calculate the product-level demand for a certain product variant, the proportion of each product variant in the actual aggregate-demand need to be generated. As an illustration, assuming that each type of material has five options and aggregate-level demand is 16,875 units, the procedure to generate proportion of each product variant is illustrated in figure 5.6.

As shown in figure 5.6 the proportion of a specific product variant is generated in several stages. The sequence for generating the proportion of material is made arbitrarily. In the model, the proportion of product requiring different packaging requirement is generated first. Then the proportion of product requiring a certain type of main material is generated. Finally, the proportion of product requiring a certain type of unique material is calculated. The product-level demand is calculated by multiplying these proportions with the actual aggregate-level demand.

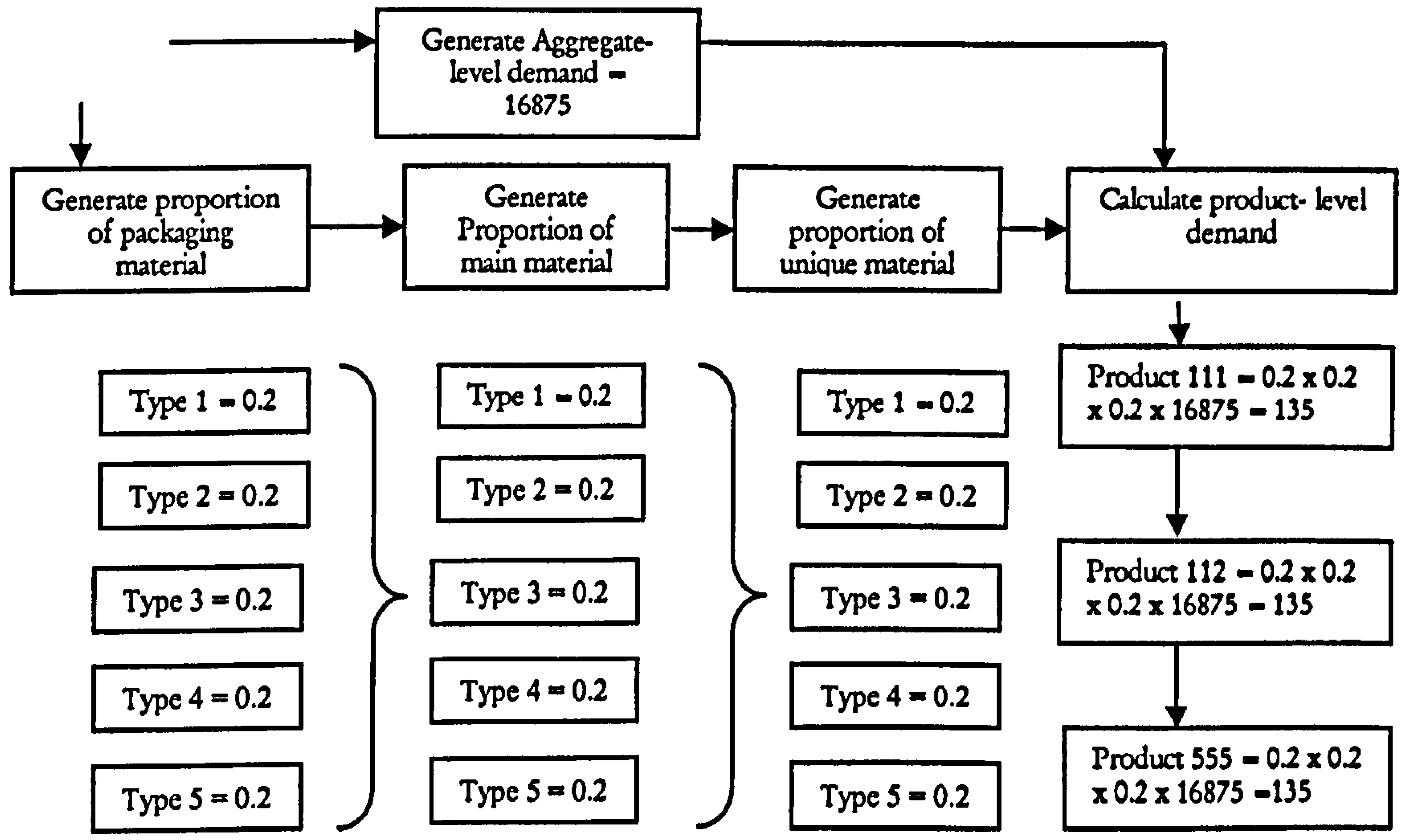


Figure 5.6 An illustration on the procedure for generating proportion of product variants

The uncertainty in product-level demand is generated by assigning different values to the parameters representing the proportion of main, unique and packaging materials for each product variant when product-level demand is constant or variable.

5.7.2.1 Constant product-level demand (constant product mix)

When constant product-level demand is desired, the proportion of each type of material constituting proportion of a certain product variant is given a deterministic value that remains constant from one period to another.

5.7.2.2 Variable product-level demand (uncertain product mix)

When variable product-level demand is desired, the proportions of materials constituting certain product variants in one period are generated using a statistical distribution. Parameters to control both types of product-level demands will be justified in the following section. The product mix for the forecasts in period i+1, i+2, i+3, i+4 that is necessary to purchase the right materials is generated using the product mix of actual demand as a 'base'. The simplest situation is to assume that product mix for the forecast i+1, i+2, i+3, i+4 equals to the product mix of actual demand.

5.7.3 Batch generation

The simulation study is investigating the impact of different levels of product variety. In the maximum variety situation, the system will produce whatever level and mix of product-level demand requested by the customer. However, when the system produces less than maximum variety, each product-level demand is divided into several batches before being scheduled for production. As the size of a transfer batch is assumed to be the same as the process batch, it is simply referred as batch. The size of the batch will be determined in section 5.8.

5.7.4 Production schedule

After the batches are generated for each product-level demand, the manufacturer has to generate a certain scheduling rule in order to determine the sequence of production of each batch. It is assumed that the production control system aims to minimise the time that each product spends in the system i.e. average flow time. When the system produces more than one type of product variant, one way to minimise flow time is by minimising set-up. As product-level demand is generated at the beginning of the month, the schedule can be developed to minimise the set-up.

The scheduling rule used takes into account several factors including the time (month) a batch was generated and the set-up time required to process the different main material and unique material. The aim is to ensure that batches generated earlier are given the priority to be processed first. The next factor that needs to be considered is the sequence of product variants (distinguished by main, unique and packaging materials) to be produced. The longest set-up time occurs when two different types of main material are produced in sequence in process 1 (the justification is discussed in section 5.8). Therefore, a rule that ensures batches with the same main material be done first in order to reduce the occurrence of set-up time in process 1 is imposed. Then, the rule attempts to sequence product requiring the same unique materials to be produced subsequently. When two jobs have the same priority (same month, main materials, and unique material specification), the batch number is used to break the tie. To translate this rule into the model, a schedule parameter is assign to each batch containing information on: 1) month the batch is generated, 2) main material required, and 3) unique material required.

5.7.5 Material Stocks

Before production starts, the availability of materials required for production of a scheduled batch is checked. A simple rule of "Order in full" is used which means **materials are assigned for a scheduled batch only when the volume is enough to satisfy the whole batch.** Materials that have been assigned to process batches are moved from stock to the process queue until they are required for production. If the quantity of materials available is not enough to produce the batch in full, then the materials are not assigned to the respective batch, which means no material waits for the batch in process queue. The amount of shortages is noted. The module checks whether the materials can be assigned to the next batch on the schedule.

The system continuously checks if there are any materials arriving from a supplier. Materials arriving from a supplier increase the stock and will trigger the release of batches delayed in the queue waiting for materials.

Each material has an independent replenishment system. A replenishment process for each type of material is conducted at the end of the month. The inventory position for each type of materials is calculated based on inventory on hand, shortages and inventory in transit (materials currently in transport). For each type of materials, depending on its lead-time, the replenishment system will retrieve the information from the forecast to calculate **the gross requirement** for those materials. The volume ordered for a specific material is calculated as follows:

$$\text{Order to supplier} = \text{Gross requirement} - \text{Inventory position} \tag{5.10}$$

5.7.6 Production

To reflect the empirical findings, the manufacturing processes conducted by the manufacturer are divided into three stages namely: process 1, process 2 and process 3. We assume that the three processes are conducted in the same plant. As shown in figure 5.5, if enough material is available for the scheduled batch, the production process starts with main material entering process 1 as it becomes available. If main material is not available, the batch is delayed and must wait in *a queue waiting for main materials.* If in the preceding batch, process 1 processed a different main material option to the current batch, a major set-up is conducted before starting process 1. If the two subsequent batches used the same main material option, process 1 starts immediately.

When process 1 is finished, the module checks if there is unique materials waiting for the batch in the *queue process 2.* If no unique materials are assigned to the batch, the batch is delayed and waits in *a queue waiting for sufficient unique materials* (see sub-section 5.7.6.1 below). As process 2 becomes available, the process will check if set-up is required in process 2. Processing different types of unique material sequentially in process 2 will require a minor set up. Following this, output of process 1 is assembled with unique material.

Similarly, the output of process 2 will find the packaging materials assigned to the batch in the *queue process 3* before entering process 3. If no packaging materials are assigned to the batch, then the batch is delayed and must waits in *a queue for packaging materials.* A check for set-up is also carried out before conducting process 3. Changes in packaging requirements require a very short set-up time. Finally, finished products are assigned to satisfy the customer demand and two performance measures are collected: the average time required to finish a product (flow time) and the average level of inventory.

5.7.6.1 Scheduling of delayed jobs

In this model materials are assigned for process batches before the production. However, materials are required at different stages in the production e.g. unique material is only needed after the batch finish in process 1. This means, materials only delay production if it is not available when it is needed for production. Batches delayed due to unavailability of materials are held in a *queue waiting for materials* (see figure 5.5) with a certain scheduling rule in alignment with the schedule of production. When more materials arrive, increasing that material stock, the system releases the batch waiting for the material, starting from the job at the head of the queue through to the tail according to the order set by the scheduling rule. The batch takes the amount of materials required for production and is sent to the queue for the respective processes e.g. batch delayed due to unique materials shortages is sent to queue process 2.

5.8 Setting simulation parameters and levels of factors

While results from the empirical study provide insights in developing the structure and logic of the simulation model, no specific quantitative data is obtained that can be used as values for parameters in the model. In addition, using data from a specific company would not be consistent with the nature of the objectives of the simulation study. A set of quantitative values for input parameters of the simulation model i.e. a reference set of input data (Kritchanchai & MacCarthy, 2002), needs to be generated that are consistent with the generality of the objectives of the study here. This reference case will provide a basis for conducting simulation experiments for the factors to be investigated.

5.8.1 Setting the reference input data

In this section, the reference input data for capacity, demand, processing time, set-up time and batch size are set.

5.8.1.1 Capacity

Production capacity in this model is based on typical working hours in most companies - 8 hours/day and 5 working days/week. Thus, the model has 20 working days or 160 working hours per month. The capacity available each month is assumed to be constant. Demand that cannot be satisfied during a certain month is carried over as a backlog to the next month(s).

5.8.1.2 Demand

As described previously, there are two levels of demand considered in the model - aggregate-level and product-level. Both the aggregate-level and product-level demand are treated as experimental factors in order to investigate volume and product mix uncertainty, respectively. A **reference value** representing the level of demand and proportion of each product variant within the aggregate-level demand needs to be set in order to:

- Represent the 'normal' or 'ideal' situation when demand is assumed to be constant.

- Provide a point of comparison to analyse the impact of volume and mix uncertainty.

In setting the reference value of aggregate-level demand several points are considered:

- Findings from the empirical study indicate that, given the available capacity of 20 days per month, companies typically aim to produce a minimum of 15,000 units of product per month or 180,000 units of product per year.
- The model is designed to investigate the impact of having 1, 3 and 5 options for the (1) main material, (2) unique material and (3) packaging material. Thus, to achieve a reasonable value (i.e. integer value) for product-level demand, the aggregate-level demand should be a multiple of 3 and 5.
- In the maximum variety situation the system produces 125 different product variants. It is assumed that the volume of production for each product variant should be greater than 100. This means the aggregate-level demand should be greater than 12,500 units per month.

These considerations suggest that the aggregate-level demand should be greater than 15,000 and the value should be divisible by 3 and 5.

Taking into account the above considerations, the reference value for aggregate-level demand is set at 16,875 units per working month. This means that the product-level demand for each product variant in the maximum variety situation is 135 units per product variant, which appears to be a reasonably acceptable value.

5.8.1.3 Processing time

Based on the capacity and demand per month, the length of processing time can be determined. The system consists of three process stages - process 1, process 2 and process 3. The empirical results provide insights in determining the relative values of each stage of processing. As presented in table 5.1, process 3 typically involves packaging that requires substantially shorter processing time compared to processes 1 and 2. Process 1 typically involves fabrication and manufacturing operations and thus requires relatively longer time than process 2. Thus, the lengths of process 1, 2 and 3 are set as 50%, 40%, and 10% of the total processing time respectively.

Process 1 time > Process 2 time > Process 3 time

Process 1 = 50% total processing time

Process 2 = 40% total processing time

Process 3 = 10% total processing time

In determining the length of processing time for each process, we need to consider the 'reference' or 'normal' situation when:

a. The system produces only one type of product, thus no additional time is incurred due to set-up activities.
b. Suppliers always deliver on time, thus there are no production delays due to material shortages.

On the other hand, we also need to consider the most extreme situation when the system produces maximum variety. In this situation, a considerable amount of available capacity will be used for set-up activities. Considering the available capacity is constant, the processing time, set-up times as well as the batch size need to be set so that the available capacity is not exceeded. If the capacity in a normal situation is set too high, then in high variety situations substantial backlogs will occur due to lack of capacity and ultimately lead to *system overflow.*

Considering the two extreme situations mentioned above, we assume here that in 'normal conditions' the system aims to achieve greater than 75% capacity utilisation. Slack capacity is deliberately placed in order to cope with high variety situations.

As suggested previously, process 1 takes 50% of the total processing time. This means that process 1 is the bottleneck facility that determines the utilisation of the system. In order to achieve the target of 75% utilisation for normal operating conditions then the processing time for each process can be derived as follows:

$$\frac{\text{Processing time in process 1}}{\text{Available capacity}} = 75\%$$

$$\frac{\text{Demand x process time 1}}{\text{20 days}} = 75\%$$

16875 x process time 1 = 15 days

Processing 1/unit = 15 days/16875 unit = 0.00088 day/product

= 0.0009 day/product = **0.432 minute/product**

Process 2 = 0.0009 x (0.4/0.5) = 0.00072 day/product

= **0.3456 minute/product**

Process 3 = 0.0009 x (0.1/0.5) = 0.00018 day/product

= **0.0864 minute/product**

These values will be used in the simulation model.

5.8.1.4 Set-up time

Changes due to differences in main material are assumed to require major set-ups involving the entire production line. The empirical evidence suggests that this typically requires up to 6-8 hours. Set-ups due to unique and packaging material changes will not require lengthy processes. In the simulation system, set-up times for each process are set as follow:

Set-up time for process 1 = 6 hours = **0.75 day**

Set-up time for process 2 = 2 hours = **0.25 day**

Set-up time for process 3 = 0.5 hours = **0.0625 day**

5.8.1.5 Batch size

The size of the batch plays an important role as they affect the amount of time the product spends in the system i.e. flow time, particularly in terms of queue time and waiting time to form a batch. In determining the most plausible batch size, it is assumed that the size of transfer batch is equal to process batch. Another consideration is the different level of product variety produced by the supply chain system.

It is considered that in a maximum variety situation, particularly when demand is uncertain, product-level demand could be considerably small. Thus, **when**

the system produces maximum variety, any amount of product-level demand will be produced without dividing it into smaller batches. However, when the system produces a low or medium level of variety, product-level demand is typically quite large. If the production batch size equates the product-level demand i.e. product-level demand is not divided into smaller batches, flow time of a certain product variant is highly dependent on the size of product-level demand. This has two undesirable consequences. First, when there are insufficient materials to meet a product-level demand then production start time for the demand is delayed. This means larger product-level demand may have to wait longer to get the right amount of materials leading to longer flow time compared to smaller product-level demand. Second, as the size of process batch is assumed to be equal to transfer batch, then the bigger the product-level demand, the longer the time required before the batch is transferred to the next stage of processing. These situations may obscure the real impact of product variety. To avoid the influence of the size of product-level demand and to have more comparable results across different level of product variety, **product-level demand is divided into smaller size of batches when the system produces less than maximum variety.**

The main criteria used to justify the size of the batch when the system produces less than maximum variety are as follow:

- Process 1 is the bottleneck facility. Thus, when the system produces only one type of product while demand and supply remains constant, capacity utilisation of process 1 has to be close to 75%.

- When more than one type of product variant is produced in a constant demand and constant supply situation, the batch size has to enable the entire product-level demand to be completed within the available capacity (20 days). In other words, in the deterministic situation the batch size has to prevent continuous backlogs, as it will lead to *system overflow*.

Based on the above assumptions and criteria, three possible values were chosen, representing small, medium and large batch sizes:

- Small batch size: 135 units. This value is derived from the maximum variety situation where the system produces 125 different product variants.
- Medium batch size: 625 units. This value is derived from the medium variety situation when the system produces 27 different product variants.
- Large batch size: 3375 units. This value is derived from the situation when the system produces 5 different product variants or when the system produces only 1 product but the production is divided into 5 batches.

These values were experimented with a spreadsheet in two situations: 1) when the system produces only one product variant and 2) when the number of options of main material is five, and the system produces five different product variants. The performance of each value on both criteria set above is investigated. In order to investigate criterion 2, the completion time for the last batch is obtained as a proxy of flow time. Table 5.4 shows the utilisation and the last batch completion time obtained from each value of batch size in both situations.

Table 5.4 Capacity utilisation of each process and completion time for different batch size

Number of Prod	Batch Size	No of MM	No of UM	No of PM	Utilisation (%)			Completion Time (Day)
					Process 1	Process 2	Process 3	
1	16875	1	1	1	75.94	24.06	15.19	30.38
1	135	1	1	1	75.94	60.75	15.19	15.31
1	625	1	1	1	75.94	60.75	15.19	15.75
1	3375	1	1	1	75.94	60.75	15.19	18.23
5	135	5	1	1	75.94	60.75	15.19	19.06
5	625	5	1	1	75.94	60.75	15.19	19.73
5	3375	5	1	1	75.94	53.91	12.15	21.98

As shown in table 5.4, when the system produces only one product and the production is run in one large batch, the utilisation of process 1 is 76%. However, utilisation of process 2 and process 3 are not surprisingly very low. This is due to the fact that the items finished in process 1 have to wait until the entire batch is finished before being transferred to process 2.

When the batch size is 135 units, the utilisation of process 1 remains the same, however the utilisation of process 2 and 3 increased significantly to 61% and 16% respectively. When the batch size is increased to 625 units and 3375 units, the capacity utilisation remains the same with the small batch size. This is because all the batches are finished within the given period i.e. no backlog. However, the completion time of the last batch increases. This highlights the fact that, although the capacity utilisation remains the same, increasing the batch size means more capacity is used for non-productive activities such as waiting for a batch to be formed.

This trend is highlighted further when the number of main material options is increased to five. In this situation, if the batch size is set at 3,375 units, the capacity utilisation decreases to 54% and 12% for process 2 and process 3, respectively. This means that the larger batch sizes do not satisfy the criteria. A batch size of 625 gave similar results to 135. However, it is expected to results in worst capacity utilisation when the level of variety increases.

Based on the investigation on different values of the batch size, it is concluded that the smallest possible batch size (135 units) is the most reasonable value to adopt. Thus, when the system produces less than maximum variety, product-level demand will be divided into several batches with **a size of 135 units.** This value maximises the capacity utilisation at every stage of processing and enables demand to be completed in the fastest possible time. As we are investigating the impact of product variety, the small batch size will provide a comparable value across different levels of product variety. By assuming that process and transfer batch sizes are the same and are the smallest feasible, we are also assuming a relatively efficient and flexible plant.

5.8.1.6 Summary of reference input data

The reference set of input data is summarised in table 5.5.

Table 5.5 The reference input data used in the simulation model

Parameters	Values
Capacity	1 month = 20 days = 160 hours = 9600 minutes
Average Aggregate Demand	16875 Unit/Month
Batch Size	135 Unit of Product
Processing time	0.0018 day/product = 0.864 minute/product
Process 1	0.0009 day/product = 0.432 minute/product
Process 2	0.00072 day/product = 0.3456 minute/product
Process 3	0.00018 day/product = 0.0864 minute/product
Set-up time	
Set-up process 1	0.75 day = 360 minutes
Set-up process 2	0.25 day = 120 minutes
Set-up process 3	0.0625 day = 30 minutes

5.8.2 Setting the values for experimental factors

In addition to the input parameters, a set of reference values needs to be determined for the following **experimental factors:**

- Supply lead-time uncertainty
- Aggregate-level demand uncertainty (volume uncertainty)
- Product-level demand uncertainty (product mix uncertainty)

5.8.2.1 Setting distribution to control supply delivery time uncertainty

As suggested previously, supply lead-time is determined by the location of supplier and supplier's reliability. Results from the empirical study gave insights to the average lead-time time for suppliers located in the same country as the manufacturer (local supplier) and suppliers located in different countries (global supplier). Local suppliers are expected to deliver in 20 days. Due to the transportation that is usually done through sea shipment, global suppliers are expected to deliver in 60 days.

Pilot experiment 1 is conducted for two main purposes:

1. To investigate the impact of different levels of supply lead-time uncertainty on the performance of international supply chains.
2. To choose a good set of values for each type of supply lead-time to be used in subsequent experiments.

A triangular distribution is used to generate and control the uncertainty in supplier's lead-time. The triangular distribution is chosen simply because it allows us to control the minimum and maximum values to avoid extreme values e.g. zero or negative, which are not possible for the supply lead-time.

The level of supply lead-time uncertainty can be measured from coefficient of variation (CV). **Detailed descriptions of the pilot experiment 1 are provided in Appendix 3.**

Pilot experiment 1 has given insights on the relationships between relative values and the shape of triangular distribution, coefficient of variation and their impact on key performance measures of the model. When the shape of triangular distribution is symmetrical, the maximum CV that can be generated (for positive values) is approximately 40%, as shown mathematically in Appendix 3. A global supplier is expected to take 3 times longer to deliver than local suppliers, and therefore to generate the same level of C.V., the triangular distribution for a global supplier has to be three times wider than the spread of local suppliers.

Results of the pilot experiments suggest that increasing the CV of supply lead-time in general leads to worst performance for the system. To keep comparable results between global and local, we assume that buying from global and local suppliers have the same level of CV. However, the fact that the global suppliers are expected to take longer to deliver than local supplier will potentially lead to worst performance.

In order to investigate other phenomena, in the next stage of the experimentation, a certain level of CV will be set to represent uncertainty in the supply lead-time. Results from the pilot experiments suggest that keeping the triangular distribution symmetrical leads to more reasonable results. It also suggested that very high levels of CV lead to great disruptions in the system, leading to 'extreme' results. A CV of 30% is chosen to represent acceptable levels of uncertainty in supply lead-time. Therefore, the supply lead-time is generated from Triangular Distributions with **minimum, mode and maximum values of (5,20,35) days and (15,60,105) days for local and global suppliers, respectively.**

5.8.2.2 Setting parameters controlling aggregate-level demand uncertainty

<u>Constant aggregate-level demand</u>

As described previously, there are two different mechanisms to generate constant aggregate-level demand and variable aggregate-level demand. In the experiments where the aggregate-level demand is assumed to be constant, the monthly value of aggregate-level demand is set to be 16,875. Justification on this has been discussed previously.

<u>Variable aggregate-level demand</u>

As discussed in section 5.7.1.2, when aggregate-level demand changes from one period to another, the level of uncertainty in the aggregate level demand is controlled by the standard deviation of the error in the forecast (*ForError*). The long-term **average demand** is assumed to be equal to 16,875. The *ForError* parameter is set up as a proportion of long-term demand. For example, if we want the level of uncertainty to be 20% from the average long term demand, then the *ForError* is 16,875 x 20% = 3,375.

Having set up the average long term demand and *ForError*, the mechanism will require the values for minimum amount (x) and constant (a) for each forecast as shown in equation 5.8. For simplicity, the minimum quantity for forecasts is generated as a percentage of average long-term demand. The main guidance is that the minimum amount decreases as the forecast predicts further into the future.

For the forecast in period t+1, minimum quantity = 0.8 x 16,875 = 13,500, constant $a_1 = 0.2$ because

$$16{,}875 = 13{,}500 + 0.2\,(16{,}875) \tag{5.11}$$

For the forecast in period t+2, minimum quantity = 0.6 x 16,875 = 10,125, constant $a_2 = 0.4$ because

$$16{,}875 = 10{,}125 + 0.4\,(16{,}875) \tag{5.12}$$

When the suppliers are global, the system also generates forecasts three and four periods ahead.

For the forecast in period t+3, minimum quantity = 0.4 x 16,875 = 6,750, constant $a_3 = 0.6$ because

$$16{,}875 = 6{,}750 + 0.6\,(16{,}875) \tag{5.13}$$

For the forecast in period t+4, minimum quantity = 0.2 x 16,875 = 3,375, constant $a_4 = 0.8$ because

$$16{,}875 = 3{,}375 + 0.8\,(16{,}875) \tag{5.14}$$

In order to explore how the system performs for different levels of aggregate-demand uncertainty and justify the level of aggregate-level demand uncertainty to be used for further experimentation, **pilot experiments 2** were conducted. **More detailed descriptions on pilot experiments 2 can be found in Appendix 4.**

Results from pilot experiment 2 not only verify that the mechanism to generate demand uncertainty worked as expected, but it also suggested that increasing aggregate demand uncertainty by increasing the level of forecast error clearly leads to worse supply chain performance. Therefore, in the future experimentation, only one level of forecast error will be investigated with any other factor. The forecast error is set at 20% of the average aggregate level demand, as the result from pilot experiment suggested that this value provides a sufficiently good representation of volume uncertainty. Higher levels of uncertainty caused more extreme results that might obscure the impact of other factors.

5.8.2.3 Setting parameters controlling product-level demand (product mix)

Constant proportion of product variants

The proportion of each product variant depends on the number of different main, unique and packaging materials produced by the manufacturer. It is assumed that when product-level demand is constant, each type of material will have an equal proportion over aggregate level demand. If there are 3 different options of main material, then each option will have a proportion of 1/3 = 0.333. Similarly, when the number of options for main material is 5, each option will have a proportion of 1/5 = 0.2. Based on this logic, the proportion of each option within the aggregate-level demand is summarised in table 5.6. These values are used to generate the proportion of each product variant when there is no uncertainty in product mix.

Table 5.6. Proportion of each option of material for different numbers of material options

Number of different options of material	Proportion of each option				
	1	2	3	4	5
1	1	-	-	-	-
2	0.50	0.50	-	-	-
3	0.33	0.33	0.33	-	-
4	0.25	0.25	0.25	0.25	-
5	0.20	0.20	0.20	0.20	0.20

Variable proportion of product variants

However, we are also interested to investigate the impact of changes in product mix from one period to another on performance of supply chain. To accommodate this, instead of having a deterministic and constant value of product mix from one period to another, the proportion of a certain product variant is generated by statistical distributions. As suggested previously, the assumption is that each option of material will have equal proportions within aggregate level demand. Thus, a different number of options will lead to different proportion for each material option. In the experimentations process, there will be 2 levels of material options considered: 3 options and 5 options. For each of these levels, the distributions to generate the proportions of each material option are different. However, in order to ensure comparable results between experiments with 3 material options and 5 options, the distribution set for each level should have approximately the same level of uncertainty when measured by C.V. The most appropriate distribution parameters to control uncertainty when the system has 3 options and 5 options were achieved through conducting several trials. The distributions for mix uncertainty when the number of options is 3 and 5 are presented in table 5.7 and table 5.8, respectively.

Table 5.7. Proportion of material when the number of options is three

Material Number	Proportion of material when product mix is constant over period	Proportion of material when product mix is uncertain from one period to another				
		Distribution	Minimum	Mode	Maximum	CV
1	0.33	Triangular	0.23	0.33	0.43	0.1237
2	0.33	Triangular	0.23	0.33	0.43	0.1237
3	0.33	Determined = 1 – Σ proportion of 1 to 2 actually sampled				

Table 5.8. Proportion of material when the number of options is five

Material Number	Proportion of material when product mix is constant over period	Proportion of material when product mix is uncertain from one period to another				
		Distribution	Minimum	Mode	Maximum	CV
1	0.2	Triangular	0.15	0.2	0.25	0.1020
2	0.2	Triangular	0.15	0.2	0.25	0.1020
3	0.2	Triangular	0.15	0.2	0.25	0.1020
4	0.2	Triangular	0.15	0.2	0.25	0.1020
5	0.2	Determined = 1 – Σ proportion of 1 to 4 actually sampled				

When there are three material options, the proportions of material option 1 and 2 are sampled from the distribution shown in table 5.7. Similarly, when there are five material options, the proportions of option 1 to 4 are sampled from the distribution shown in table 5.8. In both situations, the proportion of the last material option is determined from the sum of proportions of the other materials to ensure that the total proportion of all materials equals to one. This method is chosen primarily for efficiency in modelling.

This method results in different variability across the material options. The last material option will have higher variability compared to the other material options. Despite the differences in level of variability across the material options, no significant impacts are expected on our chosen performance metrics, except for those due to simulation variation. This is due to the fact that set-up occurring due to material variety is not sequence dependent.

In order to check the potential 'bias' of the method applied on the experiment results, an alternative method of controlling the variability has been tried. The alternative method entails randomising the assignment of the last proportion across different materials, instead of always assigning it to the last material. As expected, applying the alternative method affects the changes in the proportion of each product-level demand across different periods. However, the results obtained using the alternative method show no significant differences for either average system inventory or average flow time through the system compared to the method applied in the model. The reason is that spreading the variability across different products only shifts the forecast errors from one product variant to another over the periods. This affects the level of inventory of individual materials. However, we are looking at the **inventory at a system level i.e. the total inventory**. The main factor affecting flow time is delays that occur due to shortages of material. Applying the new methods only shifts the shortages and delays from one product to another, which **does not influence the average flow time.**

Having explained the logic of the program, the next two sections will verify and validate the model.

5.9 Verification

According to Law & Kelton (2000) "verification is concerned with determining whether the conceptual simulation model (model assumptions) has been correctly translated into a computer program i.e. debugging the simulation computer program". Two techniques proposed by Law & Kelton are used in order to verify that the structure and logic in the simulation is correct and gives results as expected under predictable condition:

1. Tracing i.e. checking the state of the simulated system just after each event and comparing it with hand calculations to see if the program is operating as intended. Tracing is conducted throughout the process of developing the simulation program.
2. Running the simulation under a variety of settings of the input parameters and check if the output is reasonable. In order to apply this verification technique the simulation was run under several conditions:
   - The most deterministic or normal situation
   - Increasing product variety
   - Uncertain aggregate-level demand (uncertain volume)
   - Uncertain product-level demand (uncertain mix)

   Detailed description of verification process under these conditions can be found in **Appendix 5**. Results from the verification process confirm that the simulation program is correct and provide expected results under predictable conditions.

5.10 Validation

Law and Kelton (1991) defined validation as "determining whether the conceptual simulation model (as opposed to the computer program), is an accurate representation of the system under study". Validation involves ensuring that the model is wholly adequate and appropriate for the task for which it is intended (Pidd, 1998). Kleijnen (1995) conjectures that the perfect model would be the real system itself, so validation cannot result in a perfect model. He further argues that the model should be 'good enough' which depends on the goals of the model.

Many simulation models, particularly those based on a specific system and using actual data as input parameters, can be formally validated. However, it is not easy to do formal validation if: 1) the simulation study uses a hypothetical model, which is not based on any specific real system or 2) when real data are not adequately available. Persson & Olhager (2002), for example, developed three supply chain models to represent three different supply chain designs of a mobile communication system manufacturer i.e. the old structure, current structure and the next generation structure. The third model cannot be validated as it was defined as a preferred system and does not exist. However, the authors argue that this model is valid with respect to the purpose of the study.

Similarly, formal validation cannot be conducted in this study due to the following two reasons. Firstly, although the simulation model is developed based on four international supply networks, it sets out to capture only generic characteristics of the four cases. Secondly, the simulation experiments have not used actual data from those four cases. Although formal validation process is not possible, the model is considered to be valid or "good enough" for the purpose of the study, which intends to demonstrate inter-relationships among various factors including product variety, demand and supply uncertainty and to give approximate estimations of the impacts of those factors on the performance of international supply chains. The model and the experiments have been designed to enable greater understanding of a generic type of MNC supply network rather than one specific MNC supply network.

5.11 Tactical planning for the simulation

Once the model is verified and concluded to be valid for the purpose, the next step before conducting the simulation experiments is to make several tactical decisions regarding steady-state period, length of simulation run and number of replications.

5.11.1 Identifying warm-up period

Before starting the experiments, it is important to ensure that the results are taken when the simulation has reached a steady state (Law and Kelton, 2000). The most commonly used technique to identify the steady state is graphical observation i.e. plotting selected response variables in time series and identifying when the initial transience is over (Pidd, 1998). It is expected that different treatment conditions will affect the periods required by the system to reach a steady state. Thus, in identifying the steady state period, different conditions imposed on the system are considered.

In order to spot when the steady state occurs, the model was run for 5,000 periods (each period equalling one simulated month), on two contrasting situations as follows:

1. Normal conditions when the system produces one type of product while demand and supply are constant.

2. Highly variable when the number of main materials, unique materials and packaging materials are 5 so the system produces maximum variety while demand and supply are subject to uncertainty.

For the two conditions sets above, two measures including average flow time per unit product and average main material - type 1 - held in stock were taken and plotted. The results are shown in figure 5.7 and figure 5.8. Plots of other situations can be found in **Appendix 6**.

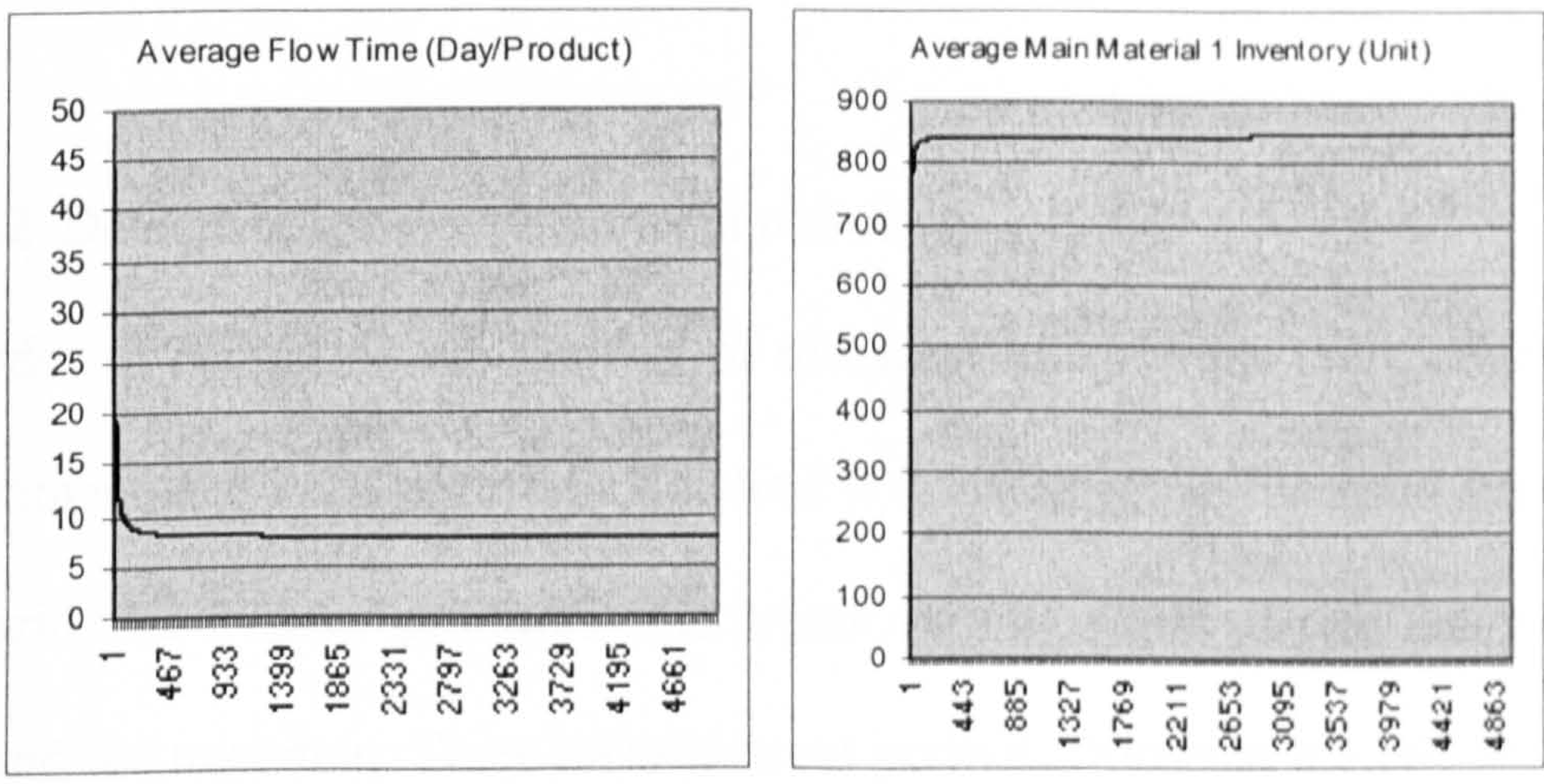


Figure 5.7 Average flow time (a) and average main material inventory (b) over 5,000 months when the system produces one type of product and demand and supply are constant

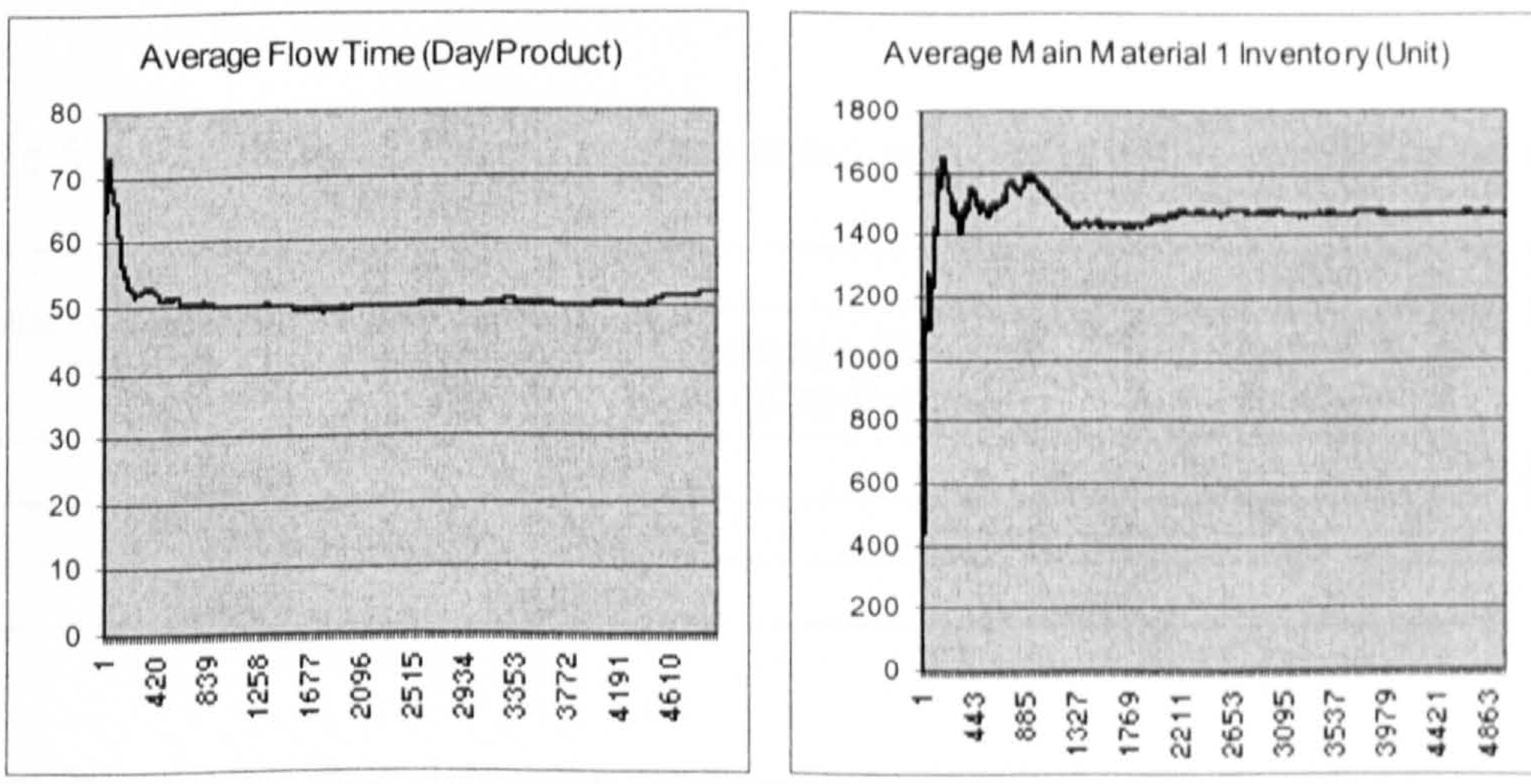


Figure 5.8 Average flow time (a) and average main material inventory (b) over 5,000 months when the system produces maximum variety while demand and supply are subject to uncertainty

The plots for every condition suggested a very clear base to identify when the system reaches a steady state. It was found from figure 5.7.a and 5.7.b that under normal condition steady state is reached before 1,000 months. As more uncertainties are introduced on the system, the system takes longer to reach a steady state (figure 5.8.a and 5.8.b). Careful observation on the plots suggested that generally, in most conditions the system has reached a steady state before 5,000 months. Thus, it appears to be justifiable to run the simulation for 5,000 warm up periods to discard the impact of initialisation then followed by measurement periods.

5.11.2 Determining the measurement period

In order to determine the number of measurement periods required in each experiment, the most uncertain situation is considered. In the most uncertain scenario the system produces maximum variety while supply as well as demand are uncertain. Three measurement periods following a 5,000 warm up period are tried. Two main measures obtained from each trial are presented in table 5.9.

Table 5.9 Result for different measurement periods in most uncertain situation

Warm-up period (Months)	Measurement (months)	Results	
		Average Flow Time (Day/Product)	Average System Inventory (Unit)
5000	5000	52.65	23888
5000	7500	51.92	23879
5000	10000	52.08	23797

Table 5.9 shows that different measurement periods led to relatively minor changes in system performance. This confirms that the system has reached a

steady state. Differences in the performances are affected mainly by random disturbances imposed on the system. As this finding represents the most uncertain scenario, it is safe to assume that a similar trend will also apply when the system is subjected to less uncertain conditions. Based on the findings, it is concluded that each experiment will be conducted with 5,000 warm up periods, followed by 5,000 measurement periods.

5.11.3 Determining number of replications

The last aspect of tactical planning that needs to be determined before running the simulation experiment is determining the number of replications. In this study, several *independent* runs of the simulation taking just a single reading from each run are conducted (Pidd, 1998) since the warm up and run length is not excessively long. In general, the more precision required from the results, the larger the number of replications (n) needs to be (Law and Kelton, 2000). When the sample size is small the confidence interval of a key performance output may be wide. Therefore, a certain smallness of the half-width of the confidence interval can be used as a target to determine the number of replications that reflect an acceptable precision.

In this study the commonly used 95% confidence interval is chosen. The half-width of 95% confidence interval was set to be less than 5% of average value of key output performance. In this way, the minimum number of replications can be calculated. Five replications are considered as a reasonable number of replications. Thus, five replications are conducted on the most uncertain situations when the system produces maximum variety, and both supply and demand are subject to uncertainty.

The results presented in table 5.10 shows that replicating the most uncertain scenario five times provide a half-width confidence interval that is less than 5% of the average key output. This means that using five replications is expected to provide a good precision of the key output. Thus each experiment that has a certain degree of uncertainty will be replicated five times.

Table 5.10 Results of five replications in most uncertain situation

Replication	Results	
	Average flow time (Day/Product)	Average system inventory (Unit)
1	52.65	23888
2	49.59	24404
3	53.23	23618
4	50.48	24273
5	51.43	23635
Average	51.47	23963
Variance	2.25	130703
Half-width of 95% confidence interval	1.86	449
Target 5% of average	2.57	1198

5.12 Concluding remarks

The aim of this chapter was to describe the development of a simulation model based on the findings from four MNC involved in the empirical study. Generic features of these four companies with respect to configuration, co-ordination and manufacturing processes are translated into the simulation environment. Description on the simulation experiments, factors and performance measures are provided. Specifying the simulation parameters and establishing values for a reference case has been carried out. Verification and validation of the model is conducted. Finally, tactical decisions before conducting the simulation experiments are described. Results from the simulation experiments are discussed in the following three chapters. Chapter 6 discusses the results from experiments investigating the impact of product variety and supply lead-time uncertainty when demand is constant. Chapter 7 describes the findings from experiments investigating the impact of product variety and demand uncertainty when supply is constant. Finally, findings from experiments investigating the impact of product variety, demand and supply uncertainty are provided in chapter 8.

Chapter 6
Investigating the Impact of Product Variety and Supply Lead-time Uncertainty

6.1 Introduction

The extent of supply and demand uncertainty facing different companies varies according to the nature of their product. Some supply chains may face high uncertainty in their supply side while their demand is relatively stable. Lee (2002) suggests that companies producing food products typically have relatively stable demand, however their supply may be highly uncertain depending on the yearly weather condition.

Among the companies involved in the empirical study, the EURO_BULB is facing a similar situation. Light bulbs can be classified as functional products. The end-customer demand for this product is relatively predictable. However, EURO_BULB procures their material primarily from Europe. As a result, they are facing a relatively high level of supply delivery uncertainty.

Levy (1995) is one of the few studies that addressed the impact of disruptions in supplier's deliveries on the performance of international supply chains. However, Levy's work investigates the issue in the context of a single product and a single company only and does not look in any detail on the issues of supply delivery performance in multi products environment. Thonemann and Bradley (2002) on the other hand, investigate the impact of increasing product variety on the performance of a certain supply chain configuration. However, they are working on a general supply chain environment that does not specifically capture the international aspects. In reality, when a company produces a wide variety of products requiring different types of material, the reliability of supplier delivery becomes more significant.

In this chapter, the simulation model is used to investigate the impact of different levels of product variety and supply uncertainty on the performance of international supply chains when demand is predictable. In order to achieve this objective, both aggregate-level and product-level demand is assumed to be constant from one period to another. Any impact demonstrated in the performance measures can be attributed to increasing product variety and supply uncertainty.

6.2 Experimental factors and levels

Two main factors to be investigated in this chapter are different sources of product variety and supply lead-time uncertainty (Table 6.1). Variety in the product mix is generated by the use of different types of material, including 1) main material, 2) unique material and 3) packaging material. Each type of material as a source of product variety has a choice of having one or five option(s). This is expected to give insights on the impact of increasing levels of product variety on the performance of the supply chain.

The second main factor investigated in this study is supply lead-time uncertainty. Different types of material as a source of product variety can be bought from either a local or global supplier. As indicated by most companies involved in the empirical study, a local supplier is expected to deliver in 1 month (20 days), with the range of delivery time of 5 to 35 days. When the suppliers are located in different countries, the lead-time not only constitutes longer transportation times, but also the possibility of long delays caused by some controllable (transportation or customs problems) or unexpected (weather, strikes, etc.) problems. Thus, global supplier is expected to deliver in 3 months (60 days) with the range of delivery time ranging from 15 to 105 days.

Table 6.1 Experimental factors in product variety and supply uncertainty experiments

No	Factors	Level	
	Sources of Product Variety	Level 1	Level 2
1	No. of different main materials	1	5
2	No. of different unique materials	1	5
3	No. of different packaging materials	1	5
	Supply Lead-time	Level 1	Level 2
4	Main material supply lead-time	Local: Triangular (5, 20, 35) days	Global: Triangular (15, 60, 105) days
5	Unique material supply lead-time	Local: Triangular (5, 20, 35) days	Global: Triangular (15, 60, 105) days
6	Packaging material supply lead-time	Local: Triangular (5, 20, 35) days	Global: Triangular (15, 60, 105) days

6.3 Input Parameters

Parameters and the values used in this set of experiments are summarised in table 6.2.

Table 6.2 Input parameters in product variety and supply uncertainty experiments

Parameters	Values
Capacity	1 month = 20 days = 160 hours = 9600 minutes
Monthly Aggregate Demand	16875 Unit
Batch Size	135 Unit of Product
Processing time	0.0018 day/product = 0.864 minute/product
Process 1	0.0009 day/product = 0.432 minute/product
Process 2	0.00072 day/product = 0.3456 minute/product
Process 3	0.00018 day/product = 0.0864 minute/product
Set-up time	
Set-up process 1	0.75 day = 360 minutes
Set-up process 2	0.25 day = 120 minutes
Set-up process 3	0.0625 day = 30 minutes

6.4 Design of simulation experiments

The aim of the experiments is to investigate the effect of increasing the number of options available for all three types of materials, namely main material, unique material and packaging material, from one to five under different levels of supply uncertainty. In achieving this objective, we focus on presenting results from key combinations of factors rather than exploring the impact of all possible combinations of factors. Therefore, we will not conduct a full factorial design of experiments. Rather, several sets of experiment representing interesting combinations of factors are selected.

As shown in table 6.3, the experiments are conducted in three main stages. The first stage consists of base case experiments. In the base case experiments, the number of options for different materials is changed from one to five under constant demand and constant supply delivery time. Results from the base case highlight the performance when the variety is increased under constant demand and supply. In the second stage, different sources of product variety are increased from having one option to five options. At the same time, supply delivery time of material is changed from 20 days to 5 – 35 days. In the last stage, the number of options is changed to five and the material as the source of product variety is bought from global suppliers that deliver within 15 – 105 days.

In stages 2 and 3, the situations where all the three types of material have one option only are excluded. Thus, there are 7 experimental cells in both stages, leading to a total of 14 cells for both stages. Each cell is replicated five times, which results in 70 experimental units in total.

Table 6.3 Design of product variety and supply uncertainty experiments

Experiment Set	Experiment No.	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
		Level Level 1 = 1 option of material Level 2 = 5 different options			Level Level 0 = Local supplier constant lead time Level 1 = Local supplier variable lead time Level 2 = Global supplier variable lead time		
Stage 1: Base case							
Base Case	1	2	1	1	0	0	0
	2	1	2	1	0	0	0
	3	1	1	2	0	0	0
	4	2	2	1	0	0	0
	5	2	1	2	0	0	0
	6	1	2	2	0	0	0
	7	2	2	2	0	0	0
Stage 2: Local Suppliers							
Local Suppliers variable Lead-time	8	2	1	1	1	1	1
	9	1	2	1	1	1	1
	10	1	1	2	1	1	1
	11	2	2	1	1	1	1
	12	2	1	2	1	1	1
	13	1	2	2	1	1	1
	14	2	2	2	1	1	1
Stage 3: Global Suppliers							
Global Suppliers Variable Lead-time	15	2	1	1	2	1	1
	16	1	2	1	1	2	1
	17	1	1	2	1	1	2
	18	2	2	1	2	2	1
	19	2	1	2	2	1	2
	20	1	2	2	1	2	2
	21	2	2	2	2	2	2

In each experimental unit, the statistics representing the supply chain performance are collected. Visual examination of the results indicates that the system has reached a steady-state condition after a 5,000 warm-up periods. Thus, each experimental unit is conducted for a warm-up period of 5,000 followed by 5,000 measurement periods. The main statistics including measures of inventory level, flow time, delay in production and tardiness of material delivery are collected.

In addition to the main experiments, several additional experiments are conducted to gain insights on the impacts of different numbers of options for each type of material. In the additional experiments, different sources of variety can have one or three options. The additional experiments will be used only for comparison purposes, so they are conducted only once and are not replicated five times.

6.5 Results and Analysis

6.5.1 Results from base cases

Results from the base cases are summarised in Table 6.4. The first column in the base case table shows the most simplistic situation when the number of options for each type of material is one. In this situation, the average time the product spent in the system i.e. average flow time is 7.78 days.

Table 6.4 Results from base case experiments

Measure	Unit of Measurement	Base Case							
		1 Product	MM (Ex. 1)	UM (Ex.2)	PM (Ex.3)	MM UM (Ex. 4)	MM PM (Ex.5)	UM PM (Ex. 6)	MM, UM & PM (Ex.7)
Average Flow Time	(Day/Product)	7.78	10.03	7.83	7.78	10.49	10.04	7.85	10.55
Average Delay due to MM	(Day/Delayed Product)	0	0	0	0	0	0	0	0
Average Delay due to UM	(Day/Delayed Product)	0	0	0	0	0	0	0	0
Average Delay due to PM	(Day/Delayed Product)	0	0	0	0	0	0	0	0
Average Main Material Tardiness	(Day/Late Delivery)	0	0	0	0	0	0	0	0
Average Unique Material Tardiness	(Day/Late Delivery)	0	0	0	0	0	0	0	0
Average Packaging Material Tardiness	(Day/Late Delivery)	0	0	0	0	0	0	0	0
Average MM inventory	(Unit of Main Material)	846	846	846	846	846	846	846	846
Average UM inventory	(Unit of Unique Material)	846	846	846	846	846	846	846	846
Average PM Inventory	(Unit of Packaging Material)	846	846	846	846	846	846	846	846
Average System Inventory	(Unit of Material)	2537	2537	2537	2537	2537	2537	2537	2537

In the subsequent cases, one or more type(s) of materials has 5 different options. The results indicate that when there is no uncertainty associated with both supply delivery and demand, only variation in main material has a significant impact on the average flow time. Increasing the number of main material option from one to five led to 29% increase in the average flow time. On the other hand, increasing the number of unique or packaging material options from one to five caused little change in the average flow time (less than 1% increase).

The impacts of using different types of material on the average flow time are influenced by several factors. Firstly, it is due to the fact that the length of set-up time varies across the different types of materials. Variation in main material requires significantly longer changeover time in comparison to variation in unique or packaging material. Secondly, the processing time for main material in process 1 is significantly longer compared to the processing time of unique and packaging material in process 2 and process 3, respectively. This makes process 1 the bottleneck station. As main material variety occurs at the beginning of the production process, extended lead-time associated with it will affect the production time of subsequent batches. In contrast, packaging material variety takes place at the last stage of the production process. Thus production of other batches in process 1 and process 2 are not affected. These arguments explain the strongly more significant impact of main material variety in comparison to other types of material variety.

Results from the base cases also showed that the average system inventory remains constant over the simulation periods. This is to be expected, because in this set of experiments product-level demand is generated as proportion of aggregate-level demand. Thus, when there are no uncertainties in demand and supply delivery, the sum of inventory of individual types of material i.e. average system inventory remains constant. As all suppliers are assumed to deliver in exactly 20 days, measures of material tardiness in the base case are zero. Furthermore, there are no shortages in production because demand is assumed to be constant. As a result, the measures of delays in production in the base case are all zero.

6.5.2 The impact of product variety and supply lead-time uncertainty

Results from the experiments under uncertain supply delivery time are summarised in table 6.5. The set of experiments is designed so that for some experiments, only delivery time for material(s) that is the source of product variety is changed from fixed period of 20 days to a certain range of time depending on the type of the suppliers. This means other materials will be delivered as expected. As can be seen in table 6.5, only material that is the source of product variety has measures of tardiness with delays in production. Measures of material tardiness and delays associated with other materials are all zero.

6.5.2.1 The impact of supply lead-time uncertainty on average system inventory

When there is uncertainty in supply delivery time, some materials might be delivered earlier than the expected time. This means that the materials have to be held in stock longer than necessary, which eventually leads to significant levels of average inventory than in the base case. When supply delivery time for material that is the source of variety is changed from a fixed period of 20 days to a certain range of delivery time, there is an increase in the average inventory for the respective material (table 6.5). The inventory level of other materials remains as in the base case. This eventually causes an increase on the average system inventory relative to the base case (figure 6.1). Different types of material have relatively similar impacts because every type of material has the same distribution of supply uncertainty.

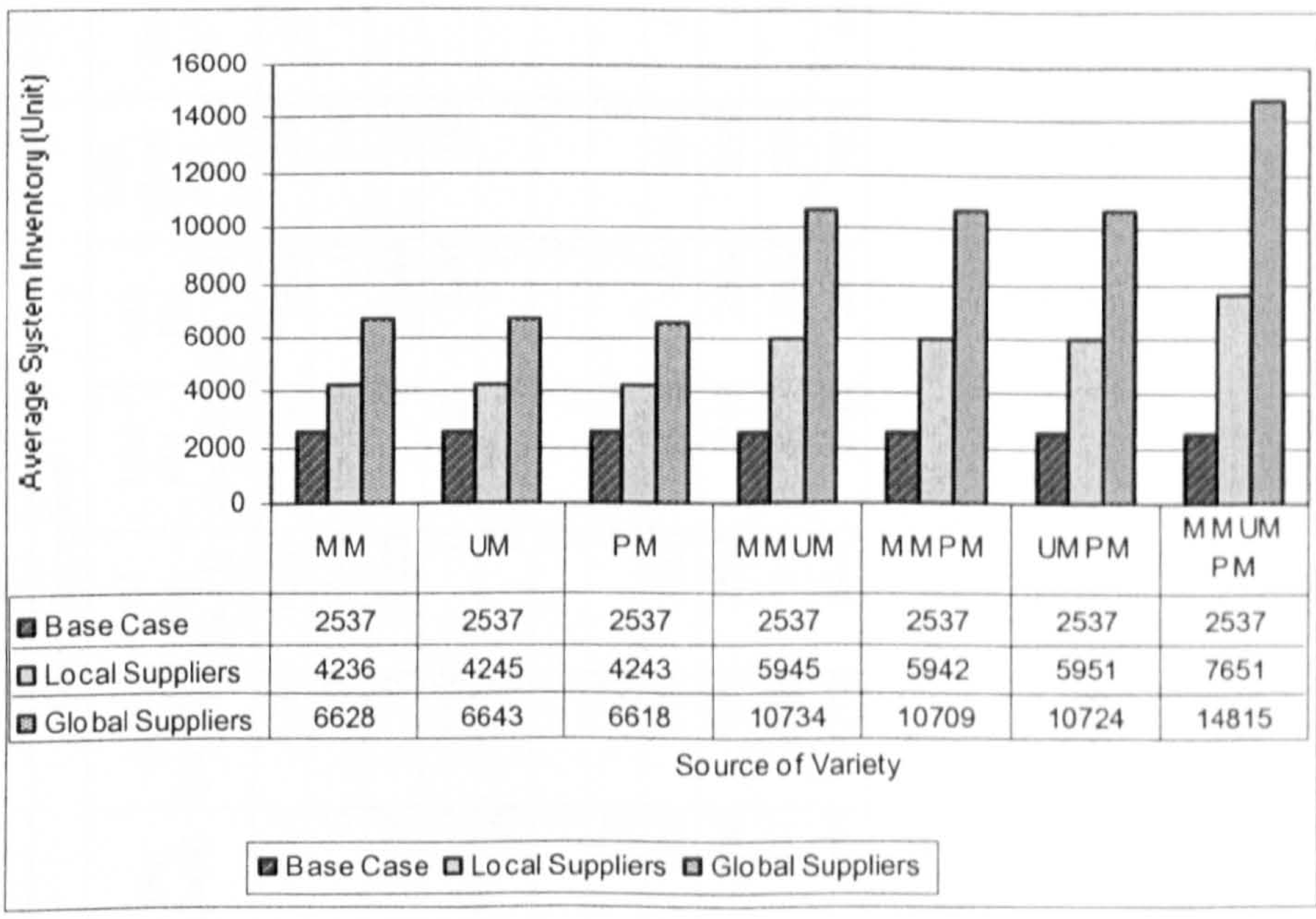


Figure 6.1 The average system inventory for different sources of variety and different ranges of supply lead-time uncertainty

As shown in table 6.6, when one type of material as the source of variety is increased from one to five options and the materials are bought from local suppliers that deliver within 5 – 35 days, the average system inventory increases approximately 67% from the base cases. If more than one source of variety have five options, then more materials might be delivered earlier than the expected time. Increasing the number of options to two and three sources of variety leads to approximately 130% and 200% increase in the average system inventory relative to the base case, respectively.

Table 6.5 Results from supply uncertainty experiments

Measure	Unit of Measurement	Local Suppliers							Global Suppliers						
		MM (Ex. 8)	UM (Ex.9)	PM (Ex.10)	MM UM (Ex.11)	MM PM (Ex.12)	UM PM (Ex. 13)	MM, UM & PM (Ex.14)	MM (Ex. 15)	UM (Ex.16)	PM (Ex.17)	MM UM (Ex.18)	MM PM (Ex.19)	UM PM (Ex. 20)	MM, UM & PM (Ex.21)
Average Flow Time	(Day/Product)	10.62	9.17	8.27	12.07	10.93	9.52	12.33	15.10	11.35	10.18	24.20	19.25	12.98	25.16
Average Delay due to MM	(Day/Delayed Product)	4.62	0	0	4.62	4.62	0	4.62	9.65	0	0	9.65	9.65	0	9.65
Average Delay due to UM	(Day/Delayed Product)	0	3.44	0	3.28	0	3.44	3.28	0	8.47	0	7.41	0	8.47	7.41
Average Delay due to PM	(Day/Delayed Product)	0	0	3.40	0	3.25	3.24	2.99	0	0	8.52	0	7.45	8.05	6.93
Average Main Material Tardiness	(Day/Late Delivery)	5	0	0	5	5	0	5	15	0	0	15	15	0	15
Average Unique Material Tardiness	(Day/Late Delivery)	0	5	0	5	0	5	5	0	15	0	15	0	15	15
Average Packaging Mat. Tardiness	(Day/Late Delivery)	0	0	5	0	5	5	5	0	0	15	0	15	15	15
Average MM inventory	(Unit of Main Material)	2545	846	846	2545	2545	845	2545	4937	845	845	4937	4937	846	4937
Average UM inventory	(Unit of Unique Material)	846	2554	846	2554	846	2554	2554	846	4952	845	4952	846	4952	4952
Average PM Inventory	(Unit of Packaging Material)	846	846	2552	846	2552	2552	2551	846	845	4927	846	4927	4927	4927
Average System Inventory	(Unit of Material)	4236	4245	4243	5945	5942	5951	7651	6628	6643	6618	10734	10709	10724	14815

Table 6.6 The impact of product variety and different level of supply uncertainty on average system inventory (unit of material) relative to the base cases

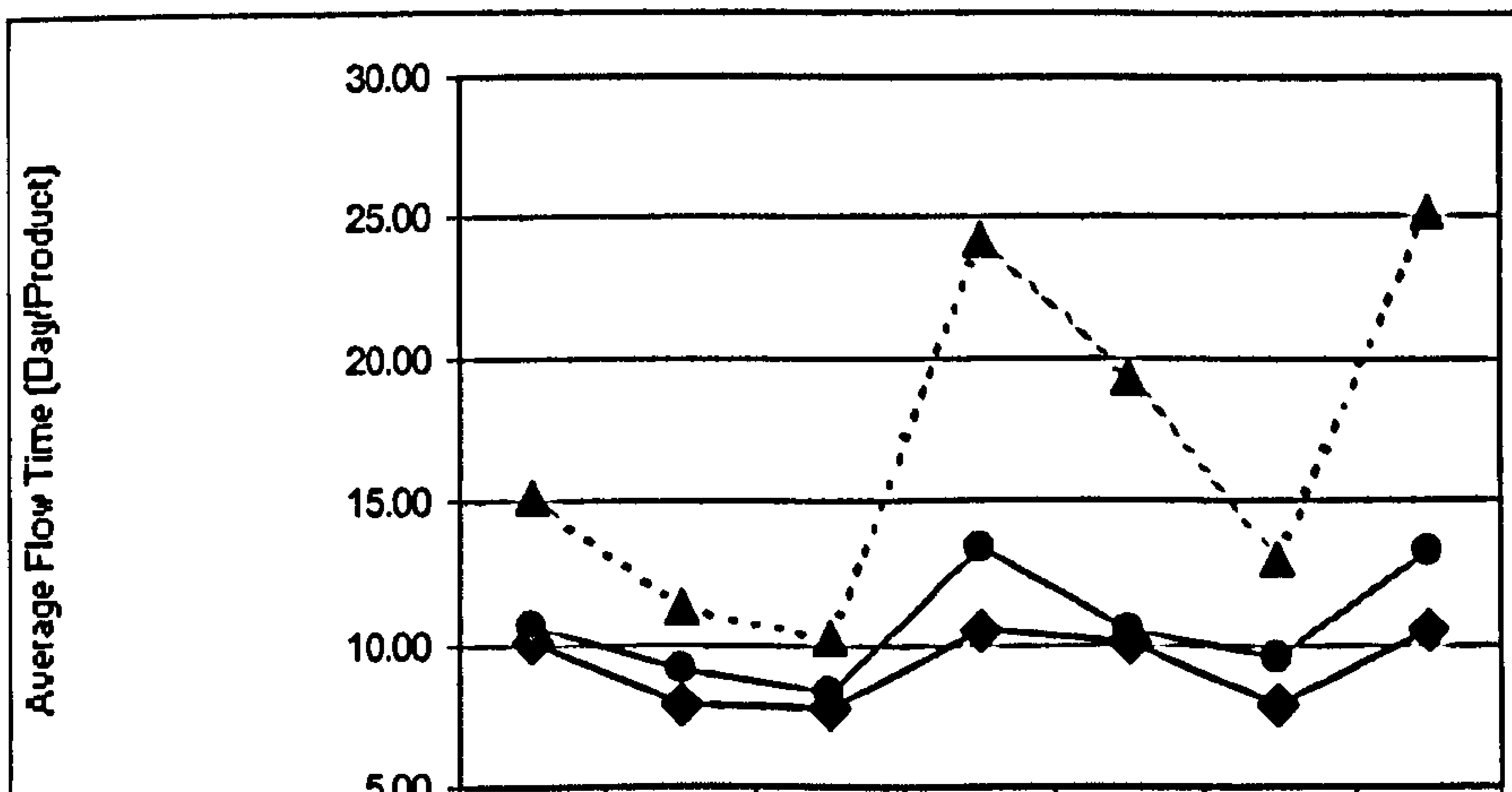
	Base Cases	Local Supplier	Increase from Base Case (%)	Global Supplier	Increase from Base Case (%)
MM Variety	2537	4236	67	6628	161
UM Variety	2537	4245	67	6643	162
PM Variety	2537	4243	67	6618	161
MM & UM Variety	2537	5945	134	10734	323
MM & PM Variety	2537	5942	134	10709	322
UM & PM Variety	2537	5951	135	10724	323
MM, UM & PM Variety	2537	7651	202	14815	484

Buying from global suppliers with greater delivery uncertainty means that there are even greater possibilities of materials delivered earlier or later than expected time. When material that is the source of variety is bought from global suppliers, the impact on the average system inventory is amplified further. As shown in table 6.6, increases in the average system inventory are in the order of 160%, 320% and 480% from the base cases when one source, two sources and three sources of variety are bought from global suppliers, respectively.

6.5.2.2 The impact of supply lead-time uncertainty on average flow time

Supply delivery uncertainty also means that a certain amount of materials might be delivered later than expected time. Lateness in material delivery causes delays in production and eventually leads to longer average flow time. Figure 6.2 shows that increasing the supply delivery uncertainty always causes longer average flow time.

Different sources of product variety caused different impact on the average flow time. As explained in the base case analysis, main material variety has higher impact on average flow time compared to unique or packaging material variety because set-up time required to produce different types of main material is significantly longer. Results from the experiment under supply uncertainty emphasised the sequence of time when materials required in production as an important factor that contributes to the different levels of impact of different sources of variety on average flow time.



	MM	UM	PM	MMUM	MMPM	UMPM	MMUM PM
Base Case	10.03	7.83	7.78	10.49	10.04	7.85	10.55
Local Suppliers	10.62	9.17	8.27	13.31	10.55	9.52	13.21
Global Suppliers	15.10	11.35	10.18	24.20	19.25	12.98	25.16

Base Case — Local Suppliers — Global Suppliers

Figure 6.2 The average flow time for different sources of variety and different range of supply lead-time uncertainty

In this experiment, suppliers for different types of material have the same supply delivery time (5 – 35 days). This range of delivery time leads to an average of 5 days material tardiness (table 6.5). However, for the same level of tardiness, different types of materials caused different magnitude of delay in production. Table 6.5 shows that 5 days lateness in main material delivery caused an average of 4.62 days delay in production. On the other hand, unique and packaging materials tardiness only causes 3.44 and 3.40 days delay in production, respectively.

These findings are logical because the materials are required at different stages in the production. The main material is required at the beginning of the production, so lateness in main material delivery is likely to delay the entire production. On the other hand, packaging material is needed at the last stage of the production. This means that lateness in packaging material delivery does not necessarily cause delays in production because process 1 and process 2 can still begin. This result confirms the importance of main material availability for production and explains why main material variety has a much more significant impact on average flow time.

The trends highlighted previously are amplified when supply delivery uncertainty increases. Buying from global suppliers that deliver within 15 – 105 days leads to 200% increase in average material tardiness (Table 6.5). As shown in table 6.7, the increase in the average main material tardiness results in 51% increase in the average flow time relative to the base case. When materials are bought from global supplier, unique and packaging material variety result in 45% and 31% increases in the average flow time relative to the base case.

A striking impact on average flow time is particularly evident when main and unique materials are the sources of product variety. When both main and unique materials are increased to five options and the materials are bought from global suppliers, the average flow time increases in the order of 131%.

Table 6.7 The impact of product variety and different level of supply uncertainty on average flow time (day/unit product) relative to the base cases

	Base Cases	Local Supplier	Increase from Base Case (%)	Global Supplier	Increase from Base Case (%)
MM Variety	10.03	10.62	6	15.10	51
UM Variety	7.83	9.17	17	11.35	45
PM Variety	7.78	8.27	6	10.18	31
MM & UM Variety	10.49	13.31	27	24.20	131
MM & PM Variety	10.04	10.55	5	19.25	92
UM & PM Variety	7.85	9.52	21	12.98	65
MM, UM & PM Variety	10.55	13.21	25	25.16	138

6.5.3 Comparing different number of options for each source of product variety

Additional experiments were conducted to compare the impact of different number of options for each source of product variety and different levels of supply uncertainty.

Figure 6.3 shows that changing the number of options for each source of variety from one to three caused less impact on the average flow time compared to changing the number of options to five. However, in general similar trends were found for different combinations of supply uncertainty and different sources of variety. Increasing the level of supply uncertainty always caused longer average flow time when the number of options is three or five.

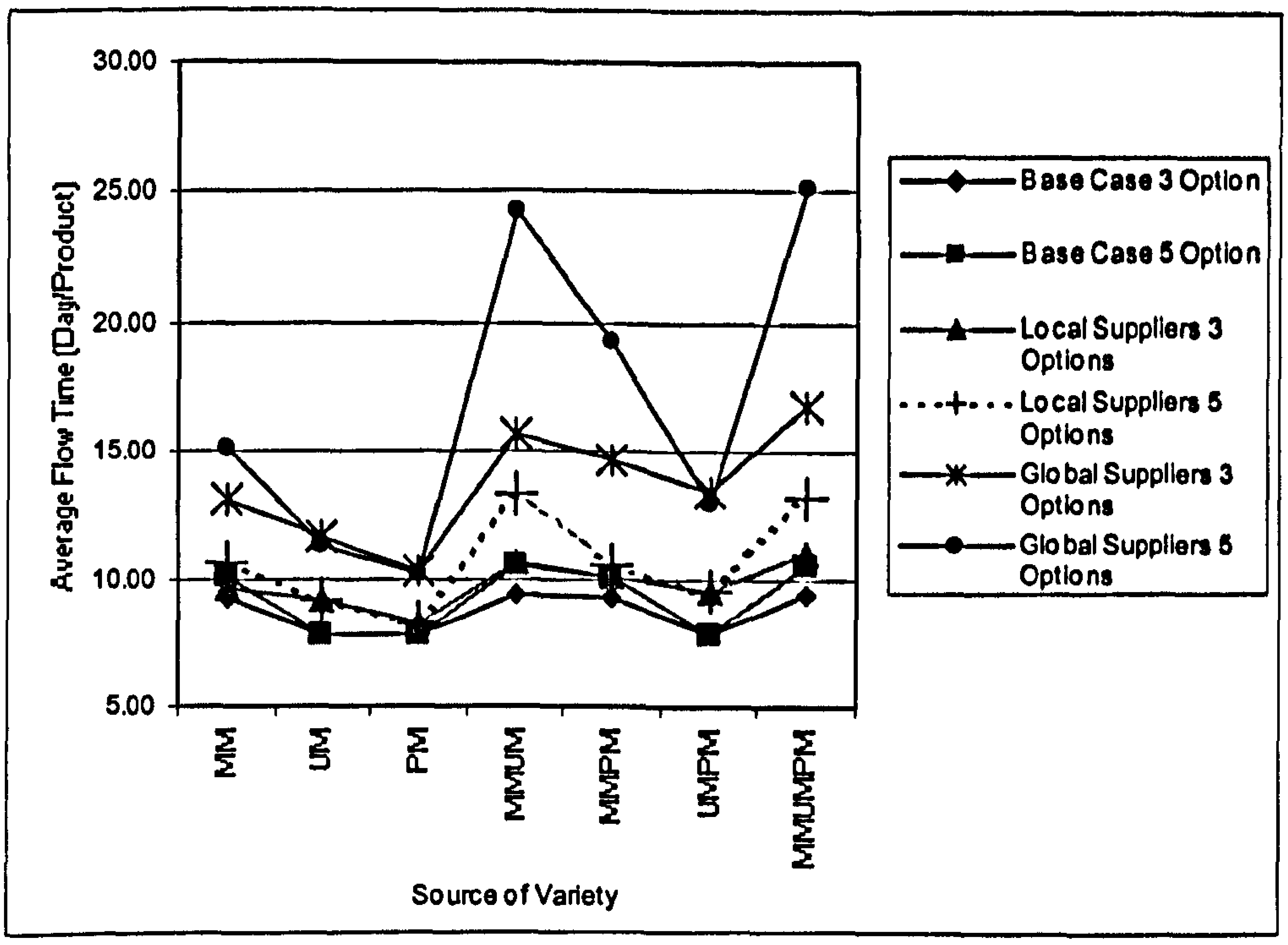


Figure 6.3 Average flow time when number of options is three and five for different range of supply delivery uncertainty

The interaction effect among different sources of product variety, the number of options for each source of product variety and supply uncertainty can be seen in the different patterns for each the line shown in figure 6.3. For the same level of supply uncertainty, only increasing the number of main material options has a significant impact on the average flow time. Increasing the number of main material options from three to five leads to 10% and 15% increase in the average flow time when suppliers are local and global respectively. Increasing the number of options of unique material or packaging material when the level of supply uncertainty is kept constant has no significant impact on the average flow time.

The impacts on average flow time are found to be evident when high number of main material option are combined with other types of material as sources of product variety under high supply uncertainty. When the system produces 125 different product variants through combinations of 5 different main, unique and packaging materials and all these materials are bought from global suppliers, the average flow time increase is in the order of 138% relative to the base case. Producing the maximum level of product variety but sourcing from local suppliers only results in a 25% increase in the average flow time.

6.6 General and practical implications

6.6.1 General implications

Important findings from obtained from this set of experiments are:

1. *The impact of supply uncertainty:* Increasing supply uncertainty leads to the worst supply chain performance both in terms of average system inventory and average flow time relative to the base case when suppliers deliver just in time. Early delivery of material means materials have to be held in stock longer than necessary, leading to a greater average system inventory. Buying material options from suppliers that deliver within 5 – 15 days results in 67% increase on the average system inventory relative to the situation when materials are delivered just in time. On the other hand, when materials are late, production will be delayed. This leads to longer average flow time.
2. *The combined impact of main material variety and buying from global suppliers:* Results from the experiments indicate that only increasing the number of main material options and buying from global suppliers have a larger impact on the average flow time. Increasing the number of main material options and buying them from global suppliers results in 51%

increase in the average flow time relative to the base case. Increasing the number of options for unique or packaging material when the level of supply uncertainty remains constant does not have a significant impact on average flow time.

3. *The combined impact of high variety and high supply uncertainty:* Combining a high number of main material options with other sources of product variety in highly uncertain supply delivery time has the most pernicious impact on the average flow time. When the number of main, unique and packaging materials options is increased and all the materials are bought from global supplier, the average flow time increases in the order of almost 140% relative to the base case.

6.6.2 Practical implications

In practice, companies may apply several strategies to mitigate the negative impact of product variety caused by variety in material requirements and supply delivery uncertainty. First, companies may adapt a strategy to reduce set-up time in bottleneck operations, product re-design or postpone their variety to reduce the impact of product variety on performance. Second, they may apply various strategies to reduce supply delivery uncertainty.

6.6.2.1 Set-up reduction

Results from the experiments show that main material variety, which requires longest set-up time compared to other sources of product variety, resulted in longer average flow time. Thus, one of the most important strategies to cope with the negative impact of product variety is to reduce set-up time. This is in alignment with findings from Anderson (1995) that severity of set-up increases manufacturing overhead cost. Thonemann and Bradley (2002) also note that in the absence of perfect manufacturing flexibility, supply chains with high variety may reduce cost by reducing set-up time.

6.6.2.2 Product re-design

Companies attempting to reduce the negative impact of variety on operations may benefit from various product-based strategies such as modular design and component sharing discussed in chapter 2. However, these efforts might be difficult to achieve as they may require a lengthy process of testing or certification and even including redesigning product and process structure. This process becomes more challenging to manage if design and development and manufacturing activities are conducted by different elements in the supply chain that are not co-located within one country. In most supply chains involved in the empirical study, design and development activities are conducted by corporate headquarters whilst manufacturing activities are conducted by manufacturers. In order to successfully re-design products or processes in the supply chain, both elements have to be actively involved in the process and good co-ordination has to be maintained.

Product redesign might be difficult to do, when component variations are driven by country-specific or other functionality requirements. One of the main sources of variety in light bulb products produced by EURO_BULB is due to different electrical attributes (voltage and wattages) required by customers in different countries. Whilst the benefit of standardising these electrical components might be significant for EURO_BULB, it would be difficult to realise as it require major changes in the well-established electrical system in different countries.

Whilst redesigning complex components that directly affect the quality of product might be difficult to conduct, standardisation of less significant parts might be more deployable. Companies producing consumer goods for regional or global markets might require a high variety of packaging materials as the language in the instructions or labels vary across different countries. To cope with this problem, many consumer goods manufacturers, such as FOOD, design a standard packaging that bears relevant information for all the designated markets. This means that the same packaging material can be used for several different markets. However, many other companies such as the European light bulb manufacturer EURO_BULB still use individual packaging for their customers in different countries. EURO_BULB might apply the standardisation strategy to reduce the different number of packaging materials required for production.

6.6.2.3 Postponed variety

In this study, variety caused by different types of materials occurs at different stages in the supply chain leading to different impacts on the average flow time. Variety caused by main materials occurs early in the supply chain causing significant delays in production. This result confirms the value of the concept of postponement widely advocated in the literature (Lee et al., 1993; van Hoek, 1999).

When the materials delivery is subject to uncertainty, postponing variation to the later stage in the supply chain means that disruption on the production due to material lateness can be minimised. Referring back to EURO_BULB case, whilst standardisation of the electrical components appears to be difficult, EURO_BULB may attempt to re-design their product and process so that incorporation of the different electrical attributes into the product can be postponed to the later stage in production.

6.6.2.4 Reducing supply uncertainty

Reducing supply uncertainty can be achieved in several ways: 1) arranging service level agreements between manufacturer and buyer, 2) introducing penalty costs for late deliveries, 3) risk pooling, 4) increasing safety stock for important items (Lee et al., 2002), and 5) localisation of supply base.

These strategies are particularly important for materials that are key to the production. In this study, the main material has the most significant implications on the average flow time. Ideally, this type of material has to have a higher service level compared to other materials. However, achieving an optimal service level agreement potentially needs substantial managerial and administrative efforts. The agreement process generally incurs some overhead costs that might increase as the range of the variety increases. In a less co-ordinated environment, some firms might apply penalty clauses for late deliveries of materials to their supplier.

Lee (2002) suggests that in order to tackle some of the problems associated with supply uncertainty, companies might utilise strategies aimed at pooling and sharing resources in a supply chain so that the risks in supply chain disruption can also be shared.

Another strategy to cope with supply uncertainty is to increase the safety stock of its key component. Some companies involved in the study suggested that they maintain a certain level of stocks for materials that are key to production. However, they admitted that they sometimes have to maintain a very high level of stocks that become very costly.

Another strategy to reduce delivery uncertainty is to buy from a more reliable supplier. In this study we assume that buying from global suppliers involves greater uncertainties in delivery times. Thus, procuring from local suppliers might reduce some of the uncertainties and increase the service level. Although most companies involved in the empirical study admitted that they are aiming to have a significant local supply base, buying certain types of material from local supplier is not always feasible. In some of the companies involved in the empirical study, certain main and 'important' materials require a very high standard of quality. In most cases this means that the main materials can only be bought from suppliers that have been approved by corporate headquarters despite the location of the supplier. Thus, the next possible option is to source less important materials such as unique or packaging materials locally. Although having less impact than main material, sourcing these materials locally may reduce some of the uncertainties in the system. The system shows worst performance when it has to cope with maximum variety and at the same time has to buy from global suppliers.

6.7 Conclusion

In this chapter we have investigated the impact of increasing the level of different sources of variety and supply uncertainty when demand is constant. Results from the simulation study indicate that producing high product variety in an international supply chain environment is a challenge that has to be addressed carefully. Producing a high level of product variety when there is uncertainty in delivery of materials required to produce the different product variants, even when the aggregate demand remains constant, always leads to longer average flow time. Within a certain level of variety, greater uncertainty in supply delivery time contributes to longer average flow time. The most notable impact is found when main material is the source of product variety and this material is bought from global suppliers. While aggregate demand remains constant, increasing product variety does not affect the average system inventory. The average system inventory is significantly affected by the level of supply uncertainty. Producing maximum variety and buying from global suppliers had the most significant impacts on the performance of the international supply chain.

Chapter 7
Investigating the Impact of Product Variety and Demand Uncertainty

7.1 Introduction

The previous chapter presents the impact of product variety and supply uncertainty under predictable demand situation. This chapter deals with the opposite situation for product variety where demand is uncertain and supply is relatively stable. Lee (2002) suggested that companies producing fashion apparel products tend to have mature and stable supply process. However, short life cycle of product means that companies involved in this sector have relatively uncertain demand.

Among companies investigated in the empirical study, INTIMATE_WEAR appears to be in this situation. INTIMATE_WEAR's supply process is relatively mature and stable. Furthermore, they procure materials for production in their own manufacturing units primarily from regional suppliers in Europe. Thus, the supply delivery uncertainty is relatively low. However, INTIMATE_WEAR produces various types of ladies underwear for several selling seasons in a year. The company finds it very difficult to predict which of their product, particularly in terms of colour, style and size, is going to sell.

Most studies on supply chain look at the problem of demand uncertainty at the aggregate-level (Levy, 1995). When a company produces a wide range of product, with different product variants requiring different types of material, it would be beneficial to investigate the impact of demand uncertainty not only at the aggregate-level but also at the product-level. Fisher et al. (1994) suggested that it is more difficult to predict demand at the product-level. This suggests that errors at product-level forecasts are likely to be greater and their potential impact on the supply chain might be underestimated. The simulation experiments presented in this chapter particularly aim to gain insights on the potential impact of uncertainty associated with product-level demand on international supply chain performance.

7.2 Experimental factors and levels

Factors that are investigated in this chapter and their levels are summarised in table 7.1.

Table 7.1 Experimental factors in product variety and demand uncertainty experiments

No	Factors	Level	
	Sources for Product Variety	**Level 1**	**Level 2**
1	No of different main material	1	5
2	No of different unique material	1	5
3	No of different packaging material	1	5
	Demand Uncertainty	**Level 1**	**Level 2**
4	Mix Uncertainty	Constant = Proportion of each material option = 0.2	Variable = Proportion of material option 1 - 4 = Triangular (0.15,0.2,0.25) Proportion of material option 5 = 1 - Σ proportions of option 1 to 4
5	Volume Uncertainty	Constant = 16,875 unit per month	Variable =* Demand = Forecast (i-1,1) + error N(0,3375) Forecast (i+1) = 13,500 + 0.2 x demand Forecast (i+2) = 10,125 + 0.4 x demand

**) Refer to section 5.8.2.2 Setting parameters controlling aggregate level demand uncertainty*

The first main factor is different sources of product variety. As the setting of variety factor used in chapter 6, each type of material can have one option or five options. The second factor is demand uncertainty, which is classified into:

1) product-level demand uncertainty (*mix uncertainty*), 2) aggregate-level demand uncertainty (*volume uncertainty*), and 3) Combination of both product-level demand and aggregate-level demand uncertainty (*combination of volume and mix uncertainty*). Parameters controlling different class of demand uncertainty have been presented and justified in chapter 5.

7.3 Input parameters

Important parameters and the associated values used in the simulation experiment are summarised in table 7.2.

Table 7.2 Input parameters in product variety and demand uncertainty experiments

Parameters	Values
Capacity	1 month = 20 days = 160 hours = 9600 minutes
Average Aggregate Demand	16875 Unit/Month
Batch Size	135 Unit of Product
Processing time	0.0018 day/product = 0.864 minute/product
Process 1	0.0009 day/product = 0.432 minute/product
Process 2	0.00072 day/product = 0.3456 minute/product
Process 3	0.00018 day/product = 0.0864 minute/product
Set-up time	
Set-up process 1	0.75 day = 360 minutes
Set-up process 2	0.25 day = 120 minutes
Set-up process 3	0.0625 day = 30 minutes
Supplier Type	Local
Supply lead-time	20 days

7.4 Design of simulation experiments

The aim of the experiments is to investigate the effect of increasing the number of options available for all three types of material, namely main material, unique material and packaging material, from one to five under different types of demand uncertainty. The simulation experimentation is conducted in three stages (table 7.3). In the first stage, the number of material options (factor 1-3) is increased from one to five under uncertain product mix condition. This means only product-level demand varies from one period to another while the aggregate-level demand is kept constant. The opposite situation is examined in the second stage. Here, the product variety factor is combined with uncertainty in aggregate-level demand while product-level demand is assumed to be constant. Finally, the situation where both aggregate-level and product-level demand are uncertain is examined in the final stage. In all stages, the situations where all the three types of material have one option only are excluded. Thus, there are 7 experimental cells in each stage, leading to a total of 21 cells for all stages. Each cell is replicated five times, which results in 105 experimental units.

Table 7.3 Design of product variety and demand uncertainty experiments

Experiment Set	Experiment No.	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
		Level Level 1 = 1 option of material Level 2 = 5 different options			Level Level 1= constant Level 2= variable	Level Level 1= constant Level 2= variable
Stage 1: Mix Uncertainty						
One Source of Variety	1	2	1	1	2	1
	2	1	2	1	2	1
	3	1	1	2	2	1
Two Sources of Variety	4	2	2	1	2	1
	5	2	1	2	2	1
	6	1	2	2	2	1
Three Sources of variety	7	2	2	2	2	1
Stage 2: Volume Uncertainty						
One Source of Variety	8	2	1	1	1	2
	9	1	2	1	1	2
	10	1	1	2	1	2
Two Sources of Variety	11	2	2	1	1	2
	12	2	1	2	1	2
	13	1	2	2	1	2
Three Sources of variety	14	2	2	2	1	2
Stage 3: Volume and Mix Uncertainty						
One Source of Variety	15	2	1	1	2	2
	16	1	2	1	2	2
	17	1	1	2	2	2
Two Sources of Variety	18	2	2	1	2	2
	19	2	1	2	2	2
	20	1	2	2	2	2
Three Sources of variety	21	2	2	2	2	2

The same protocols as in the previous experiments are followed in this set of experiments. The main statistics collected are measures of inventory level, flow time, delay in production and tardiness of material delivery for 5,000 periods following a 5,000 warm-up periods. In addition to the main experiments, additional experiments are conducted in order to compare the impact of different number of options for each source of product variety. The same experimental factors and input parameters as those in the main experimentation are used in running the additional experiments. The difference between the main and additional experiments is that in additional experiments the number of options for each source of variety is increased from one to three instead of five. These experiments are used only for comparative purposes, therefore each treatment is conducted only once without replication.

7.5 Results and analysis

Results obtained from the simulation experiments are presented in tables 7.4 and 7.5. As the supply delivery time is assumed to be constant, measures of material tardiness are zero and omitted from both tables. In analysing the results, the base case results presented in chapter 6 are used as a point of reference.

The analysis focuses on investigating the impacts of product variety and different classes of demand uncertainty on two main performance measures, namely, the average system inventory and average flow time. For each measure, the impact of different sources of product variety in uncertain demand situation is discussed. The different impact caused by different types of demand uncertainty on the two supply chain performance metrics is also analysed. The final analysis investigates the potential impact of different number of options for each source of product variety on the performance of the supply chain.

Table 7.4 Results from base case and mix uncertainty experiments

Measure	Unit of Measurement	Base case								Product variety and mix uncertainty						
		1 Product	MM (Ex. 1)	UM (Ex.2)	PM (Ex.3)	MM UM (Ex. 4)	MM PM (Ex.5)	UM PM (Ex. 6)	MM, UM & PM (Ex.7)	MM (Ex. 1)	UM (Ex.2)	PM (Ex.3)	MM UM (Ex. 4)	MM PM (Ex.5)	UM PM (Ex. 6)	MM, UM & PM (Ex.7)
Average Flow Time	(Day/Product)	7.78	10.03	7.83	7.78	10.49	10.04	7.85	10.55	22.80	9.60	9.03	23.25	22.35	9.44	22.86
Average Delay due to MM	(Day/Delayed Product)	0	0	0	0	0	0	0	0	19.00	0	0	19.00	19.00	0	19.00
Average Delay due to UM	(Day/Delayed Product)	0	0	0	0	0	0	0	0	0	9.64	0	1.03	0	9.32	2.63
Average Delay due to PM	(Day/Delayed Product)	0	0	0	0	0	0	0	0	0	0	9.52	0	2.00	6.98	2.27
Average MM inventory	(Unit of Main Material)	846	846	846	846	846	846	846	846	2968	845	846	2967	1913	846	1852
Average UM inventory	(Unit of Unique Material)	846	846	846	846	846	846	846	846	845	2992	846	1906	845	1898	1401
Average PM Inventory	(Unit of Packaging Material)	846	846	846	846	846	846	846	846	845	845	2965	846	2961	2960	2914
Average System Inventory	(Unit of Material)	2537	2537	2537	2537	2537	2537	2537	2537	4659	4683	4656	5719	5719	5704	6167

Table 7.5 Results from volume uncertainty, and volume-mix uncertainty experiments

Measure	Unit of Measurement	Product variety and volume uncertainty							Product variety, volume and mix uncertainty						
		MM (Ex. 8)	UM (Ex.9)	PM (Ex.10)	MM UM (Ex.11)	MM PM (Ex.12)	UM PM (Ex. 13)	MM, UM & PM (Ex.14)	MM (Ex. 15)	UM (Ex.16)	PM (Ex.17)	MM UM (Ex. 18	MM PM (Ex.19	UM PM (Ex. 20	MM, UM & PM (Ex.21)
Average Flow Time	(Day/Product)	24.58	12.47	11.36	25.32	24.52	12.40	25.87	25.13	13.03	11.71	25.61	24.52	12.83	25.38
Average Delay due to MM	(Day/Delayed Product)	19.00	19.00	19.00	19.00	19.00	19.00	19.00	19.01	19.00	19.00	19.01	19.00	19.00	19.00
Average Delay due to UM	(Day/Delayed Product)	3.19	9.91	0	3.58	3.40	10.30	3.52	3.10	9.54	0	3.62	3.32	10.06	3.33
Average Delay due to PM	(Day/Delayed Product)	0	0	9.83	3.00	4.03	5.47	2.91	0	0	9.50	3.07	4.26	6.67	3.77
Average MM inventory	(Unit of Main Material)	3089	2945	2947	3068	3100	2937	3046	3927	2916	2938	3905	3100	2949	3203
Average UM Inventory	(Unit of Unique Material)	2947	3086	2947	3068	2965	3075	3046	2948	3913	2938	3258	2959	3274	3048
Average PM Inventory	(Unit of Packaging Material)	2947	2945	3089	2930	3100	3075	3046	2948	2916	3906	2926	3926	3911	3851
Average System Inventory	(Unit of Material)	8982	8975	8983	9067	9164	9087	9137	9823	9744	9782	10089	9984	10133	10102

7.5.1 Impact of demand uncertainty on average system inventory

Demand uncertainty causes a certain degree of forecast error and eventually leads to disparity between material ordered and actual production requirements. On some occasions, forecasts overestimate the actual demand. Thus, materials ordered by the manufacturer are greater than the actual production requirement to satisfy demand from the customers. This means there are excess materials that have to be held longer than necessary. On the other hand, when forecasts underestimate the actual demand, shortage of material will occur. In the situation when on-hand inventory is insufficient, the production of a batch will be delayed. In this case, on-hand inventory will be held until adequate material to start the production of a certain batch in full is available. These situations eventually lead to higher average system inventory.

As shown in figure 7.1, every class of demand uncertainty results in greater average system inventory relative to the base case. The impacts caused by different type of materials as source(s) of product variety on average system inventory are relatively similar. This is logical, because in this experiment the parameters used to generate demand uncertainty is the same for every source of product variety. The slight differences found in some of the impacts caused by different sources of product variety are due to random effects.

When more than one type of material are the sources of product variety, there is an increase on the average system inventory. However, it is obvious from figure 7.1 that combination of more than one sources of variety does not have purely additive impact. The combined impact of more than one source of variety on the average system inventory is less than the sum of the impact of individual source of product variety.

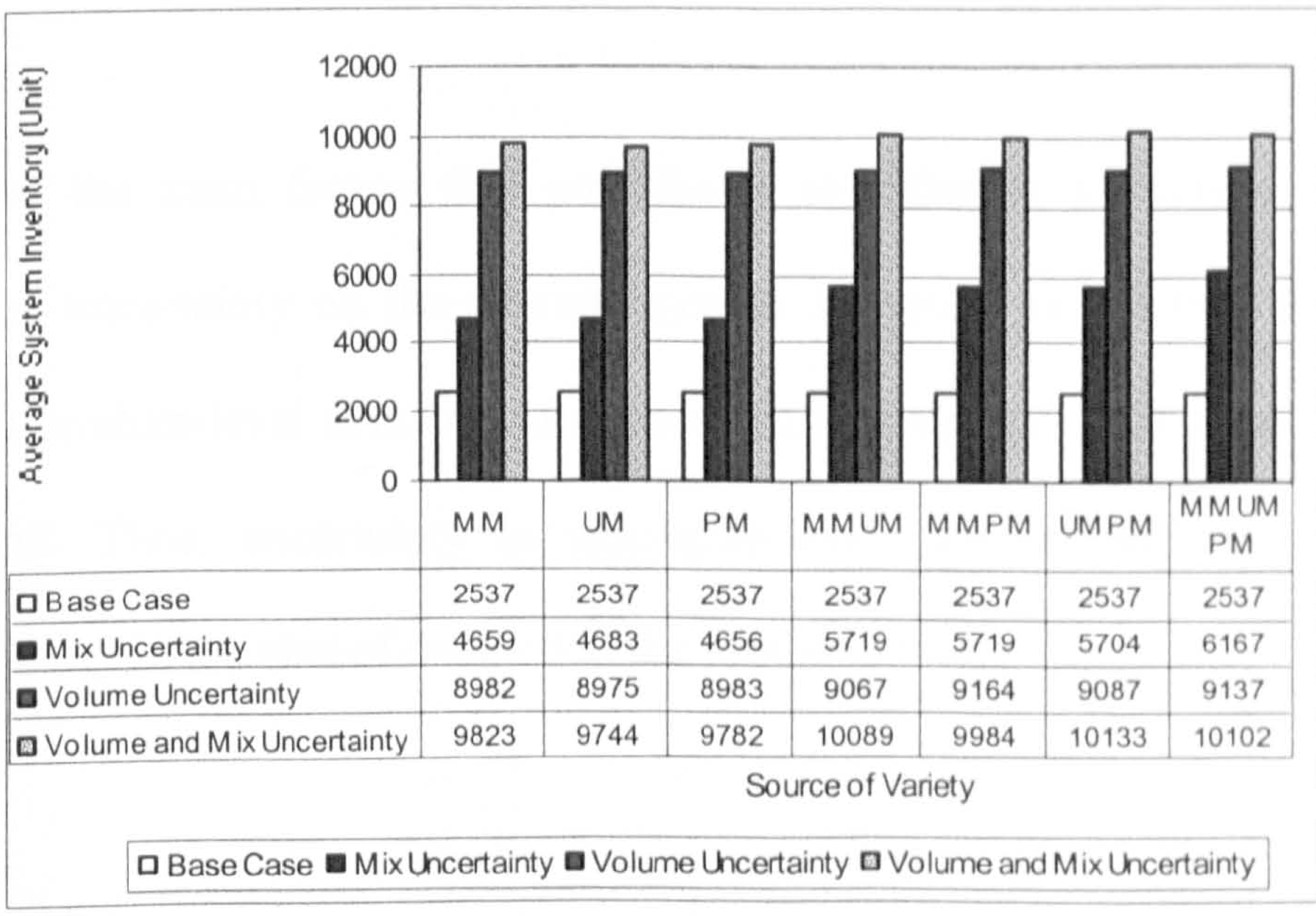


Figure 7.1 The impact of increasing product variety and demand uncertainty on the average system inventory

Table 7.6 The impact of product variety and different classes of demand uncertainty on average system inventory (unit of material) relative to the base cases

	Base Cases	Mix Uncertainty	Increase from Base Case (%)	Volume Uncertainty	Increase from Base Case (%)	Volume & Mix Uncertainty	Increase from Base Case (%)
MM Variety	2537	4659	84	8982	254	9823	287
UM Variety	2537	4683	85	8975	254	9744	284
PM Variety	2537	4656	84	8983	254	9782	286
MM & UM Variety	2537	5719	125	9067	257	10089	298
MM & PM Variety	2537	5719	125	9164	261	9984	294
UM & PM Variety	2537	5704	125	9087	258	10133	300
MM, UM & PM Variety	2537	6167	143	9137	260	10102	298

More noticeable impacts with respect to average system inventory are found across different classes of demand uncertainty. For every source(s) of product variety, volume uncertainty has greater impacts on the average system inventory compared to mix uncertainty. As shown in table 7.6, mix uncertainty results in an increase in the average system inventory that ranges from 84% - 143%, while volume uncertainty results in an increase that ranges from 254% - 261% relative to the base case.

One of the main factors that contributes to different impacts of mix and volume uncertainty on the average system inventory is the fact that in this model product-level demands are generated as proportions of aggregate-level demand. Thus, uncertainty in aggregate-level demand will also generate uncertainty in the size of demand at the product level.

When uncertainty is only associated with product-level demand, it would only affect the availability of materials that are the source of product variety. Other materials that are not the source of variety will be available as predicted. For example, when main material is the only source of variety, the system produces: product type 111, 121, 131, 141 and 151. This means that the manufacturer needs to buy main material types 1 - 5, unique and packaging materials type 1 based on forecast. Changes in product mix will affect only the requirements of main materials. Requirements for unique and packaging material will not be affected, as the five different products will need the same types of unique and packaging material. Since there is no aggregate-demand uncertainty, the total requirements of unique and packaging materials remain constant over the period. As shown in table 7.4, results from the situation with mix uncertainty show that the average of inventory levels only change for materials that are the source of variety, while the average of inventory for other materials remains constant as in the base case.

When uncertainty is associated with aggregate-level demand, the requirements of all types of material are subject to uncertainty. This means that the probability of production being delayed due to material unavailability is higher resulting in higher inventory level. Table 7.5 shows that the inventory level for all materials increases relative to the base case.

In general, the impact of a combination of volume and mix uncertainty on the average system inventory is relatively higher compared to volume uncertainty. However, combination of volume and mix uncertainty does not result in purely additive impacts. In other words, the combination of volume and mix uncertainty is less than the sum of the individual impact of volume and mix uncertainty. The relative differences between the impact of volume uncertainty and volume-mix uncertainty on average system inventory for every source of product variety are in the range of 9 - 11%. This again highlights the previous explanation that volume uncertainty also in the end results in changes of the absolute demand for each product type. Thus, combining volume and mix uncertainty does not result in stronger impacts on both measures of the supply chain.

7.5.2 Impact of demand uncertainty on average flow time

Forecast errors caused by demand uncertainty also affect the average flow time. As suggested previously, if there is a shortage in material, then the production of a certain batch will be delayed until sufficient materials arrive. In this set of experiments, it is assumed that supplier deliver in fixed period of 20 days. This means production will be delayed for approximately 20 days until the next delivery arrives. This eventually leads to longer average flow time. As shown in figure 7.2, every class of demand uncertainty results in longer average flow time compared to the base case.

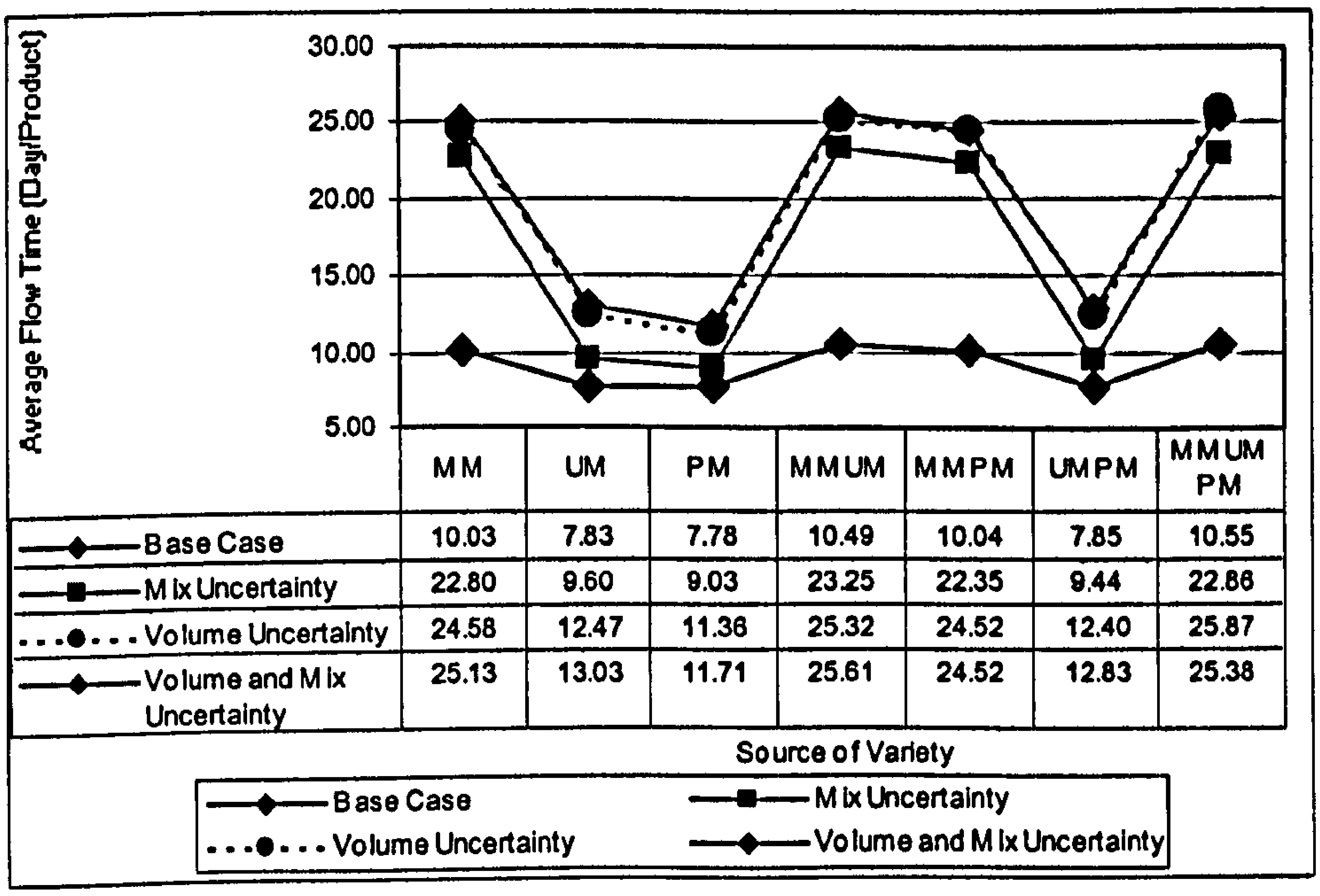


Figure 7.2. The impact of increasing product variety and demand uncertainty on the average flow time

Table 7.7 The impact of product variety and different classes of demand uncertainty on average flow time (day/unit product) relative to the base cases

	Base Cases	Mix Uncertainty	Increase from Base Case (%)	Volume Uncertainty	Increase from Base Case (%)	Volume & Mix Uncertainty	Increase from Base Case (%)
MM Variety	10.03	22.80	127	24.58	145	25.13	151
UM Variety	7.83	9.60	23	12.47	59	13.03	66
PM Variety	7.78	9.03	16	11.36	46	11.71	51
MM & UM Variety	10.49	23.25	122	25.32	141	25.61	144
MM & PM Variety	10.04	22.35	123	24.52	144	24.52	144
UM & PM Variety	7.85	9.44	20	12.40	58	12.83	64
MM, UM & PM Variety	10.55	22.86	117	25.87	145	25.38	141

As explained previously, different sources of product variety have relatively similar impacts on average system inventory. However, with respect to average flow time, significant differences are found across different sources of product variety. It is clear from figure 7.2 that main material variety has the greatest impact on average flow time among different sources of product variety in uncertain demand situations. Main material variety leads to an increase in average flow time in the order of more than 100% relative to the base case in each class of demand uncertainty (Table 7.7). Variation in unique and packaging material caused increases in the average flow time that range from 23 – 66% and 16 – 51% relative to the base case.

The different impacts caused by different source of product variety on average flow time have been discussed in the base case analysis (chapter 6). It has been highlighted that main material variety entailed longer set-ups. Main material availability is more significant to production compared to unique or packaging materials because: 1) the time to process main material is longer and 2) it is needed at the beginning of the production. When combined with uncertain demand situations, errors in predicting main material requirements have more pernicious impacts on average flow time, delaying all the subsequent batches.

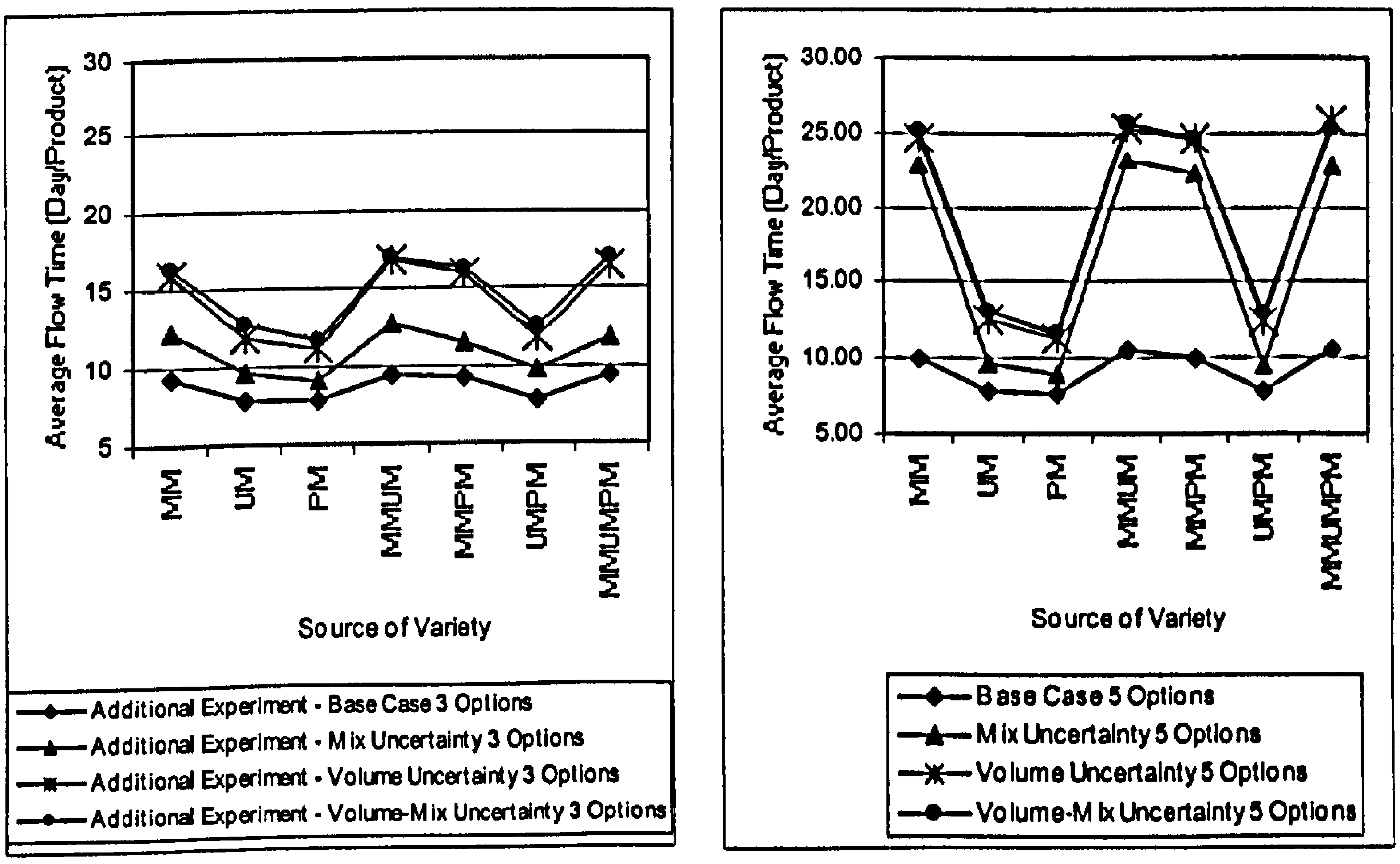
These findings also indicate that demand uncertainty and different sources of product variety have a substantial interaction impact. Demand uncertainty amplifies the different impacts of different sources of product variety on the average flow time. Demand uncertainty results in a substantial increase in the average flow time when main material is the source of product variety, but it results in only minor increases when unique or packaging material is the source of product variety.

With respect to the impacts caused by different classes of demand uncertainty, mix uncertainty has less impact on average flow time compared to volume uncertainty. As shown in table 7.7, mix uncertainty results in an increase in the average flow time that ranges from 16% - 127%, while volume uncertainty causes an increase that ranges from 46% - 145% relative to the base case for different sources of product variety. As explained in the previous section, this is due to the fact that uncertainty in aggregate-level demand affects the requirements of the entire materials, while uncertainty associated with product-level demand only affects the requirements of materials that are the sources of product variety. When volume is uncertain, there are greater possibilities of production being delayed due to material shortages. Table 7.4 shows that under mix uncertainty, delays only occur due to shortages in materials that are the sources of product variety. However, different results were found in uncertain volume situation. For example, results from experiment 15 where main material is the source of variety in uncertain volume situation (Table 7.5) shows that there are 19 days/product and 3.19 days/product delays in production due to shortage in main and unique material, respectively.

The impacts of combining volume and mix uncertainty on average flow time are significantly less than the sum of the individual impacts of volume uncertainty and mix uncertainty. The relative differences between the impacts of volume uncertainty and combination of volume and mix uncertainty for any source(s) of product variety are less than 5%.

7.5.3 Comparison of different number of options for each source of product variety

Additional experiments were conducted to compare the potential impact of different number of options for each source of product variety. Comparison on the results from additional experiments and main experiments with respect to average flow time can be seen in figure 7.3.a and 7.3.b, respectively.



(a) (b)

Figure 7.3 The average flow time for different classes of demand uncertainty when number of options is three (a) and five (b)

Overall, when the number of material options is changed from one to three, the impact on the average flow time is less than when the number of material options is changed from one to five. One clear difference between figure 7.3.a and 7.3.b is the fact that the lines representing different classes of demand uncertainty in figure 7.3.a are relatively parallel to the line representing the base case. This indicates that although demand uncertainty increases the average flow time for every source of product variety, there are very little interaction effects between different classes of demand uncertainty and different sources of product variety. Thus, the different impacts across different sources of product variety in every classes of demand uncertainty are relatively the same.

On the other hand, strong interaction effects between different sources of product variety and demand uncertainty are found in figure 7.3.b. As discussed previously, when the number of material options varies between one and five, the impact of main material variety is amplified significantly, while the impact of unique and packaging material variety are considerably less. These results imply that with respect to average flow time, interaction effects not only exist between different sources of product variety and demand uncertainty, but also among sources of product variety, level of product variety (number of options for each source of variety) and demand uncertainty.

Apart from the above differences, comparison across different classes of demand uncertainty for each source of variety shows similar trends between 3 options and 5 options experiments. Mix uncertainty caused smaller impact on average flow time compared to volume uncertainty. The combination of volume and mix uncertainty does not have a purely additive impact on average flow time.

However, increasing the number of main material options from three to five appears to have significant impact in the uncertain mix situation. When the number of main material options is three, the difference between mix uncertainty and volume uncertainty is quite significant (30%). However, when the number of main material is increased to five, the difference between the impacts of mix uncertainty and volume uncertainty is only 8%. These results suggest that the different impacts of mix uncertainty and volume uncertainty diminish as the number of main material options increases. When the number of main material options is high (5 options), the impact of mix uncertainty is almost as pernicious as volume or volume mix uncertainty.

Results from the additional experiments demonstrate that increasing the number of options for different types of material might have different impact on the average flow time. Thus, more detailed experiments to investigate the impact of different number of options for different types of material might provide interesting findings.

7.6 General and practical implications

7.6.1 General implications

Some important findings are obtained from these sets of experiments:

1. *The impact of demand uncertainty*: demand uncertainty affects the supply chain operations as it leads to mismatch between materials ordered and actual demand.
    - When forecasts overestimate actual demand, the system will have to carry excess inventory longer than necessary.
    - On the other hand, if forecasts underestimate actual demand then shortage of material occurs. In this situation, production has to wait until sufficient material to run the production of a batch becomes

available. This eventually leads to a higher average of system inventory and average of flow time compared to the base cases where demand is constant.

2. *The impact of mix uncertainty*: based on the uncertainty level set for the experiments, mix uncertainty results in a smaller impact on both measures of the supply chain performance compared to volume uncertainty. Mix uncertainty results in an increase in the average inventory that ranges from 84 - 143% while volume uncertainty results in an increase that ranges from 254 - 261%. Similarly, volume uncertainty results in an increase in average flow time that ranges from 46 – 145%, compared to an increase in the range of 16 – 127% caused by mix uncertainty. This is because:
   - Product-level demand is generated as a proportion of aggregate-level demand, which means changes in aggregate-level demand will also lead to changes in the absolute demand in the product-level.
   - Product-level demand uncertainty only affects provisions of materials that are the sources of variety, while changes in aggregate-level demand will affect the provisions of all materials.

3. *The combined impact of volume and mix uncertainty*: Although the combined impact of volume and mix uncertainty on both measures of the supply chain performance is higher than the impact of volume uncertainty, the combination of volume and mix uncertainty does not have a purely additive impact.

4. *Different impacts of demand uncertainty on two performance metrics*: when demand is uncertain, different sources of product variety have relatively similar impacts on average system inventory. However, different

impacts are found on the average flow time. In any class of demand uncertainty, main material variety has the greatest impact on average flow time. This is due to the fact that main material variety requires longer set-ups compared to other sources of variety. Secondly, main material variety occurs early in production leading to significant impact on subsequent processes in the supply chain. For each type of demand uncertainty, the increase in the average flow time due to main material options is in the order of over 100%, while unique material and packaging material variety only result in increases that range from 23 – 66% and 16 – 51%, respectively.

5. *Amplification effects of different source of variety*: the different impacts on average flow time caused by different sources of product variety are amplified by demand uncertainty. There are strong interaction effects between different sources of product variety, the number of material options and demand uncertainty. In uncertain demand situation, increasing the number of main material options constantly leads to significant increase in the average flow time. Increasing the number of options of unique material or packaging material variety has more limited impacts on the average flow time.
6. *Impact of increasing number of option of more than one source of variety*: Increasing the number of product variants by having more than one sources of variety does not have a significant impact on the average flow time. When there is more than one sources of product variety, production of a certain batch might be delayed due to shortages in one type of material but not due to shortages of all materials.

7.6.2 Practical implications

7.6.3.1 Limitations of the results

Here we have investigated the impact of increasing product variety when demand is uncertain. The study in this chapter generally captures the consequence arising from demand uncertainty that results in mismatches between material ordered and actual production requirements. More specifically, it aims to provide insights on the potential impact of product-level demand uncertainty, as it has not been widely addressed in the literature. While results from the simulation experiments satisfy these objectives, it has to be highlighted that the results might be limited on the set of parameters used in this experiments i.e. parameters used to generate mix uncertainty and volume uncertainty. This is an aspect highlighted for further study.

Another point that needs to be stressed here is that the risk associated with demand uncertainty is amplified in this chapter because of the fixed period replenishment applied in the system. With this operating policy, the manufacturer only orders once per period, and supplier will deliver within a fixed period of lead-time. This can be interpreted in two practical ways:

- From the manufacturer side, this applies when ordering cost is relatively high, which makes frequent or in-between period ordering costly.
- From the supply side, this highlights supplier inability to respond to urgent demands that come in-between periods. It can also be true when the suppliers are located far from the manufacturing unit. Thus, despite their ability to ramp-up their production to meet the order but transportation time might make it impossible to respond to the urgent orders in time.

Several companies even attempt to avoid urgent ordering as it may create nervousness to the entire supply chain.

7.6.3.2 Mitigating the negative impact of product variety

Companies producing high product variety in highly uncertain demand situation might also benefit from various strategies discussed in chapter 6. Results from this set of experiment also found that variety incurring longest set-up, i.e. main material variety, resulted in longer flow times. Thus, set-up reduction is certainly beneficial. When materials used in different products can be standardised, the impact of error in predicting demand will be less pernicious to operation.

The results also emphasise the influence of the timing of proliferation process on the average flow time. If proliferation process can be delayed until more information on demand can be obtained, the mismatch between supply based on forecast and actual production requirement can be avoided. Lee (2002) suggested that companies with a highly unpredictable demand but have a very stable process and product technology can use the concept of postponement to pursue aggressive build-to-order strategy. He identified Dell Computer as one company that has successfully applied this strategy.

7.6.3.3 Frozen Period Agreement

In reality, the elements in the supply chain might reduce some of the negative impacts caused by demand uncertainty by having agreement concerning 'frozen period' i.e. how many periods into actual production that changes are not allowed. However, this strategy is not always possible, especially when there is unequal power between the elements of the supply chain. There have to be a good relationship and a willingness to share the risks associated with demand uncertainties between the elements to achieve these types of agreement. Elements in the supply chain may benefit from the concept of partnerships widely proposed in the literature (Ellram, 1995; Slack et al., 2004; Wisner et al., 2004).

7.6.3.4 Careful inventory management

Another strategy to face demand uncertainty is to 'buffer' the system from the uncertainty through careful inventory management. First of all, the company has to recognise the types of demand uncertainty as it entails different risks such as material shortages and high inventory. If uncertainty is mainly concerning the proportion of different product variants, but aggregate-demand remains relatively constant, then a manufacturer can order common materials based on forecast. At the same time, they can try to be more flexible with the procurement of materials that become the source of variety i.e. product-specific materials. This, for example, can be done by buying product-specific materials closer to actual production period so that more information is available. This strategy will require responsive vendors that can supply just in time.

7.7 Conclusion

In this chapter we have investigated the impact of product variety when the supply chain is facing different classes of demand uncertainty while suppliers are able to deliver on time. Results from the simulation demonstrate that demand uncertainty certainly is an important factor in managing an international supply chain. In an uncertain demand situation, forecasts generated might overestimate or underestimate actual demand. Both situations lead to worst performance in terms of average flow time and average system inventory. Among different classes of demand uncertainty, mix uncertainty when aggregate-level demand remains constant has the least impact on supply chain performance, as its impacts are relatively restricted to the provision of materials specific to different product variants. Uncertainty in aggregate-level demand has a higher impact as it affects the provision of the entire materials. The results also indicate interaction effects among different sources of product variety, the number of options for each source of product variety and demand uncertainty. Increasing the number of main material options in an uncertain demand situation constantly caused significant increase in average flow time, while increasing the number of options for unique and packaging materials has a more limited impact on average flow time.

Chapter 8
Investigating the Impact of Product Variety, Supply and Demand Uncertainty

8.1 Introduction

The previous two chapters present the impact of increasing product variety when either demand or supply delivery time is subject to uncertainty. Some supply chains may face situations when both supply and demand is uncertain. Lee (2002) exemplified that companies producing high-end computers or semiconductors have to cope with highly unpredictable demand, unstable and still evolving supply processes.

The shoes manufacturer (SHOES) involved in the empirical study is facing these problems. SHOES produces a wide variety of shoes for two seasons in a year. Thus, demand is highly uncertain. Furthermore, main materials used in the production such as rawhides depend on farming yields. SHOES primarily bought materials from global suppliers. These factors exposed SHOES to high supply delivery uncertainty. As a result, SHOES is facing a great challenge in managing their supply chain. Whilst many other companies are possibly facing similar problems as SHOES, there have not been many studies that address these issues simultaneously.

This chapter aims to investigate the impact of increasing the level of product variety under uncertain demand and supply delivery time. In particular, the chapter aims to identify the significance of different factors and any interaction effects arising from combination of factors.

8.2 Experimental factors and levels

Factors that are investigated in this chapter and their levels are summarised in table 8.1. The first main factor is product variety. Variation in the product results from the use of three different types of material: 1) main material, 2) unique material and 3) packaging material. Each type of material as a source of variety has either one, three or five options representing low, medium and high variety.

Table 8.1 Experimental factors in variety, demand and supply uncertainty experiments

No	Factors	Level		
	Sources for Product Variety	Level 1	Level 2	Level 3
1	No. of different main materials	1	3	5
2	No. of different unique materials	1	3	5
3	No. of different packaging materials	1	3	5
	Supply Lead-time	Level 1	Level 2	
4	Main material supply lead-time	Local: Triangular (5, 20, 35) days	Global: Triangular (15, 60, 105) days	
5	Unique material supply lead-time	Local: Triangular (5, 20, 35) days	Global: Triangular (15, 60, 105) days	
6	Packaging material supply lead-time	Local: Triangular (5, 20, 35) days	Global: Triangular (15, 60, 105) days	
	Demand Uncertainty	Level 1	Level 2	
7	Product-level demand when number of material options is three	Constant = Proportion of each material option = 0.33	Variable = Proportion of material option 1 to 2 = Triangular (0.23,0.33,0.43) Proportion of material 3 = 1 - Σ proportions of option 1 to 2	
7	Product-level demand when number of material options is five	Constant = Proportion of each material option = 0.2	Variable = Proportion of material option 1 to 4 = Triangular (0.15,0.2,0.25) Proportion of material 5 = 1 - Σ proportions of option 1 to 4	
8	Aggregate-level demand	Constant = 16,875 units per month	Variable =' Demand = Forecast (i-1,1) + error N(0,3375) Forecast (i+1) = 13,500 + 0.2 x demand Forecast (i+2) = 10,125 + 0.4 x demand Forecast (I+3) = 6750 + 0.6 x demand Forecast (I+4) = 3375 + 0.8 x demand	

Increasing product variety can be achieved by:

1. Increasing the number of options for each source of product variety from one option to three or five options.
2. Combining more than one source of product variety.

The second factor to be investigated in this chapter is supply delivery uncertainty. Material that is the source of product variety can be bought from either a local supplier or global supplier. As suggested in the previous experiments, a local supplier is expected to deliver in 5 - 35 days, while a global supplier delivers within 15 – 105 days.

The third factor is demand uncertainty. Demand uncertainty is classified into:

1. Product-level demand uncertainty (mix uncertainty)
2. Aggregate-level demand uncertainty (volume uncertainty)

8.3 Input parameters

Important parameters and the values used in the simulation experiments are summarised in table 8.2.

Table 8.2 Input parameters in the product variety, demand and supply uncertainty experiments

Parameters	Values
Capacity	1 month = 20 days = 160 hours = 9600 minutes
Average Aggregate Demand	16875 Unit/Month
Batch Size	135 Unit of Product
Processing time	0.0018 day/product = 0.864 minute/product
Process 1	0.0009 day/product = 0.432 minute/product
Process 2	0.00072 day/product = 0.3456 minute/product
Process 3	0.00018 day/product = 0.0864 minute/product
Set-up time	
Set-up process 1	0.75 day = 360 minutes
Set-up process 2	0.25 day = 120 minutes
Set-up process 3	0.0625 day = 30 minutes

8.4 Design of simulation experiments

Results from the previous experiments are used as basis to design the experiment for this chapter. Results from additional experiments conducted in chapter 6 and chapter 7 indicate that different numbers of options for certain types of material have a potentially significant impact on the performance of the supply chain. Results from the experiments in chapter 7 highlight that a combination of volume and mix uncertainty does not have a purely additive impact. The combined impact of volume and mix uncertainty is significantly less than the sum of the individual impacts of volume uncertainty and mix uncertainty. Based on these findings, in this chapter we conduct more detailed experiments on the different number of options rather than conducting experiments on combinations of volume and mix uncertainty. The design of the simulation experimentation is presented in table 8.3.

The main experimentation is conducted in two stages, differentiated by the number of options for different sources of product variety. In the first stage, each source of variety is increased from one option to three options. In the second stage, each source of product variety is increased from one to five options. Each main stage is divided into four subsets of experiments. In each subset, different sources of product variety are combined with a certain class of demand uncertainty and a certain level of supply uncertainty. The first subset of experiments investigates the impact of increasing the number of options of different sources of product variety when mix is uncertain and materials are bought from local suppliers. This is followed by experiments investigating different combinations of product variety when mix is uncertain and materials are bought from global suppliers. The third subset investigates the impact of increasing variety when volume is uncertain and materials are bought from local suppliers. The final subset investigates the situation when volume is uncertain and materials are bought from global suppliers.

Table 8.3 Design of product variety, demand and supply uncertainty experiments

Experiment Set	Experiment No.	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8
		Level Level 1 = 1 option of material Level 2 = 3 different options Level 3 = 5 different options			Level Level 1 = Local supplier variable lead time Level 2 = Global supplier variable lead time			Level Level 1= Constant mix Level 2 = Variable mix	Level Level 1= Constant volume Level 2 = Variable volume
Stage 1: Three Options for Each Source of Variety									
Mix Uncertainty & Local Suppliers	8.1	2	1	1	1	1	1	2	1
	8.2	1	2	1	1	1	1	2	1
	8.3	1	1	2	1	1	1	2	1
	8.4	2	2	1	1	1	1	2	1
	8.5	2	1	2	1	1	1	2	1
	8.6	1	2	2	1	1	1	2	1
	8.7	2	2	2	1	1	1	2	1
Mix Uncertainty & Global Suppliers	8.8	2	1	1	2	1	1	2	1
	8.9	1	2	1	1	2	1	2	1
	8.10	1	1	2	1	1	2	2	1
	8.11	2	2	1	2	2	1	2	1
	8.12	2	1	2	2	1	2	2	1
	8.13	1	2	2	1	2	2	2	1
	8.14	2	2	2	2	2	2	2	1
Volume Uncertainty & Local Suppliers	8.15	2	1	1	1	1	1	1	2
	8.16	1	2	1	1	1	1	1	2
	8.17	1	1	2	1	1	1	1	2
	8.18	2	2	1	1	1	1	1	2
	8.19	2	1	2	1	1	1	1	2
	8.20	1	2	2	1	1	1	1	2
	8.21	2	2	2	1	1	1	1	2
Volume Uncertainty & Global Suppliers	8.22	2	2	2	1	1	1	1	2
	8.23	2	1	1	2	1	1	1	2
	8.24	1	2	1	1	2	1	1	2
	8.25	1	1	2	1	1	2	1	2
	8.26	2	2	1	2	2	1	1	2
	8.27	2	1	2	2	1	2	1	2
	8.28	2	2	2	2	2	2	1	2
Stage 2: Five Options for Each Source of Variety									
Mix Uncertainty & Local Suppliers	8.29	3	1	1	1	1	1	2	1
	8.30	1	3	1	1	1	1	2	1
	8.31	1	1	3	1	1	1	2	1
	8.32	3	3	1	1	1	1	2	1
	8.33	3	1	3	1	1	1	2	1
	8.34	1	3	3	1	1	1	2	1
	8.35	3	3	3	1	1	1	2	1
Mix Uncertainty & Global Suppliers	8.36	3	1	1	2	1	1	2	1
	8.37	1	3	1	1	2	1	2	1
	8.38	1	1	3	1	1	2	2	1
	8.39	3	3	1	2	2	1	2	1
	8.40	3	1	3	2	1	2	2	1
	8.41	1	3	3	1	2	2	2	1
	8.42	3	3	3	2	2	2	2	1
Volume Uncertainty & Local Suppliers	8.43	3	1	1	1	1	1	1	2
	8.44	1	3	1	1	1	1	1	2
	8.45	1	1	3	1	1	1	1	2
	8.46	3	3	1	1	1	1	1	2
	8.47	3	1	3	1	1	1	1	2
	8.48	1	3	3	1	1	1	1	2
	8.49	3	3	3	1	1	1	1	2
Volume Uncertainty & Global Suppliers	8.50	3	1	1	2	1	1	1	2
	8.51	1	3	1	1	2	1	1	2
	8.52	1	1	3	1	1	2	1	2
	8.53	3	3	1	2	2	1	1	2
	8.54	3	1	3	2	1	2	1	2
	8.55	1	3	3	1	2	2	1	2
	8.56	3	3	3	2	2	2	1	2

Each experimental treatment explained above is replicated five times leading to a total of 280 experimental units. As in the previous two chapters, the main statistics, measures of inventory level, flow time, delay in production and tardiness of material delivery, are collected for 5,000 periods following a 5,000 warm-up periods.

8.5 Results and analysis

The complete results obtained from the experiments can be found in the **Appendix 7**. In analysing the results, the base case results presented in chapter 6 will be used as a point of reference. The analysis of the results will be divided into two main sections. Each section is focused on investigating the impact of product variety, supply uncertainty and demand uncertainty on two supply chain performance measures: average system inventory and average flow time. Each section specifically attempts to investigate:

1. The impact of supply and demand uncertainty relative to the base case in situations with medium and high numbers of options.
2. The impact of increasing numbers of options for each source of variety in every combination of supply and demand uncertainty.
3. The impact of different sources of product variety.

In addition to the above analysis, the interaction effect of increasing supply uncertainty in a certain class of demand uncertainty and any source of variety will be investigated. This analysis is beneficial because implementing a policy to buy from local or global supplier is arguably a more deployable strategy in order to reduce the negative impacts faced by the supply chain compared to, for example, changing the type of demand uncertainty.

8.5.1 The impact of increasing product variety, supply uncertainty and demand uncertainty on the average of total inventory

Figures 8.1.a and 8.1.b demonstrate the impact of two levels of supply uncertainty and different classes of demand uncertainty on the average system inventory when the number of options is three and five, respectively.

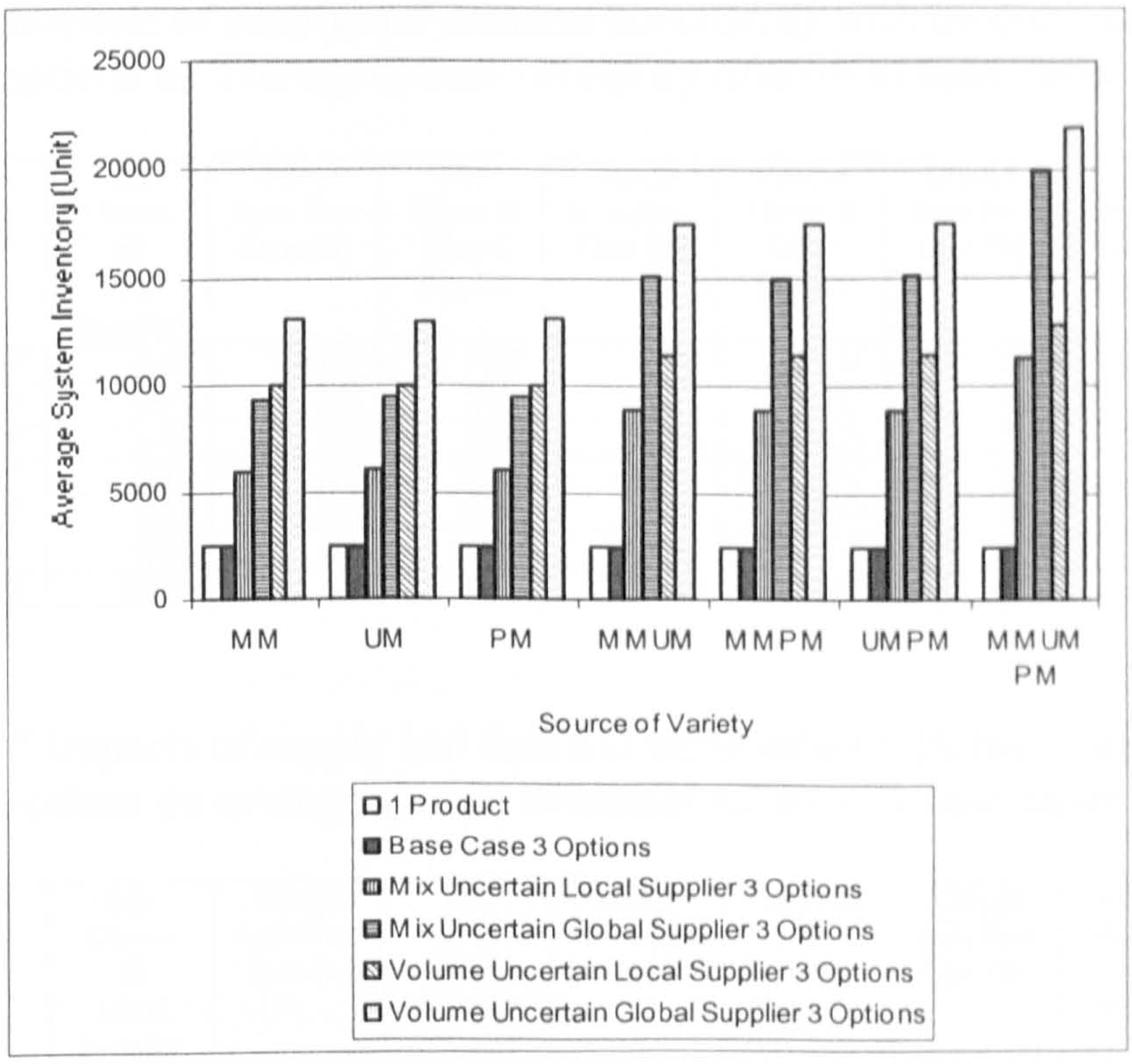
For both a medium and high number of options, every combination of supply uncertainty and demand uncertainty results in a significant increase in the average system inventory relative to the base case. This is because:

1. Supply delivery uncertainty leads to some situations where materials are delivered earlier than expected. Consequently, in this situation materials have to be held longer than necessary.
2. Demand uncertainty means that forecasts sometimes overestimate actual demand. In this situation, materials ordered are greater than actual demand leading to excess inventory.

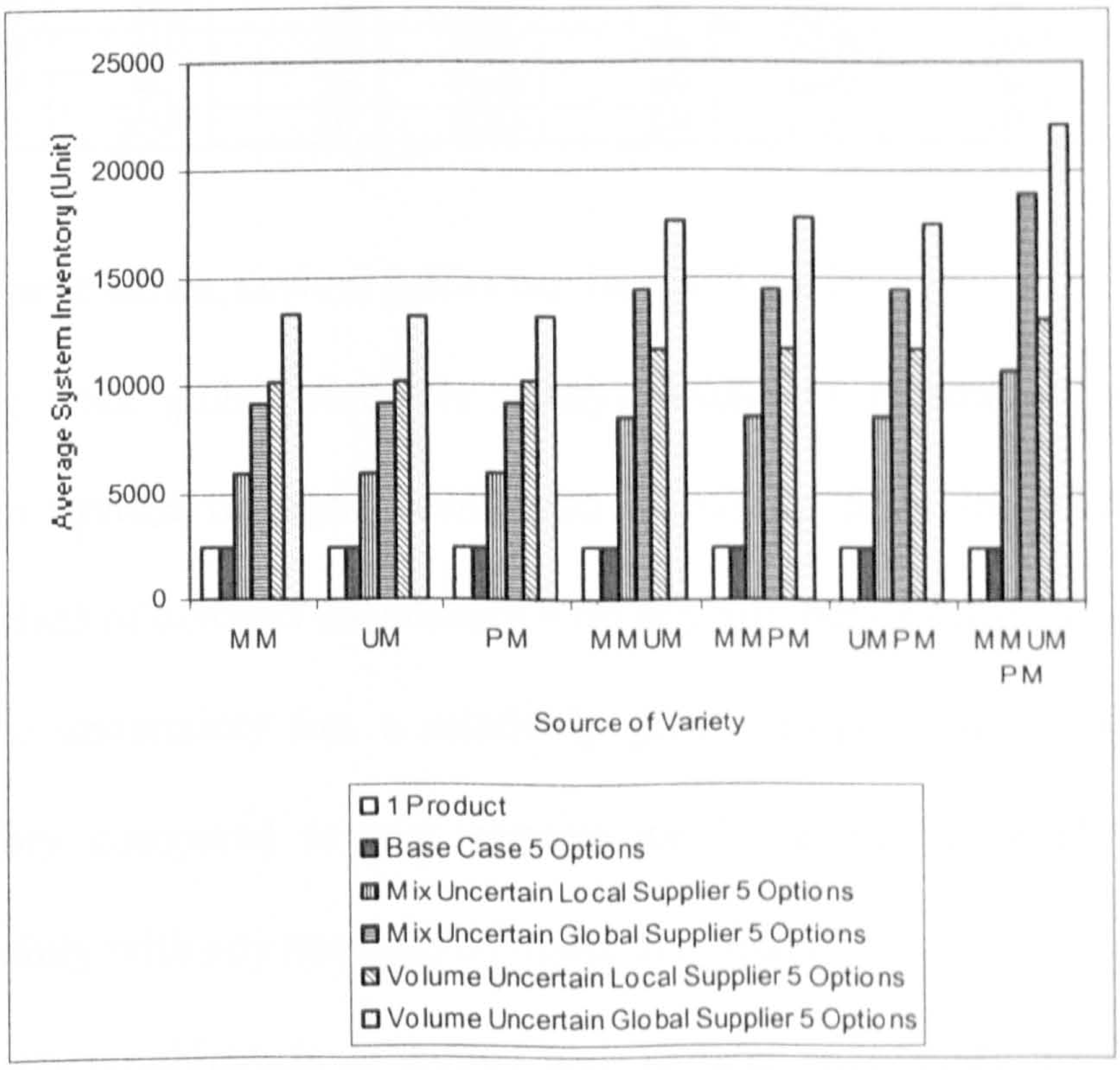
Both of the situations mentioned above contribute to greater average system inventory compared to situations when materials are available in the right amount at the right time.

8.5.1.1 The impact of supply and demand uncertainty on average system inventory relative to base case

Tables 8.4 and 8.5 present the impacts of different combinations of supply and demand uncertainty with medium and high number of options for each source of product variety on average system inventory, respectively. The percentage of changes from the associated base case is also given.



(a)



(b)

Figure 8.1 The impact of supply and demand uncertainty with a medium number of options (a) and high number of options (b) on the average system inventory

Table 8.4 Impacts of supply and demand uncertainty with medium number of options on average system inventory relative to base cases

Source of Product Variety	Base Case	Mix Uncert. & Local Supplier	Change from Base Case (%)	Mix Uncer. & Global Supplier	Change from Base Case (%)	Volume Uncer. & Local Supplier	Change from Base Case (%)	Volume Uncer. & Global Supplier	Change from Base Case (%)
MM	2537	6067	139	9407	271	10112	299	13127	417
UM	2537	6081	140	9450	273	10117	299	13045	414
PM	2537	6086	140	9537	276	10121	299	13138	418
MMUM	2537	8882	250	15018	492	11430	351	17397	586
MMPM	2537	8883	250	15014	492	11455	352	17513	590
UMPM	2537	8896	251	15024	492	11517	354	17484	589
MMUMPM	2537	11281	345	20001	688	12809	405	21882	763

Table 8.5 Impacts of supply and demand uncertainty with high number of options on average system inventory relative to base cases

Source of Product Variety	Base Case	Mix Uncert. & Local Supplier	Change from Base Case (%)	Mix Uncer. & Global Supplier	Change from Base Case (%)	Volume Uncer. & Local Supplier	Change from Base Case (%)	Volume Uncer. & Global Supplier	Change from Base Case (%)
MM	2537	5962	135	9248	265	10223	303	13262	423
UM	2537	5982	136	9252	265	10225	303	13184	420
PM	2537	5960	135	9241	264	10204	302	13147	418
MMUM	2537	8532	236	14430	469	11614	358	17568	592
MMPM	2537	8533	236	14367	466	11653	359	17726	599
UMPM	2537	8522	236	14380	467	11587	357	17506	590
MMUMPM	2537	10579	317	18865	644	13055	415	22100	771

Based on these tables, several points can be concluded:

1. Buying from global suppliers always results in greater impact on the average system inventory compared to buying from local supplier for every class of demand uncertainty with any number of material options.
2. Volume uncertainty has a relatively greater impact on average system inventory compared to mix uncertainty for a certain level of supply uncertainty with any numbers of material options.
3. For every combination of supply and demand uncertainty investigated in these experiments, increasing the number of options for any sources of product variety from one to three options or one to five options results in relatively similar impacts on average system inventory. This suggests that increasing the number of options does not have a significant impact on

average system inventory. The increases in the average system inventory shown in these experiments are caused by supply and demand uncertainty.

4. Comparing the impact of supply and demand uncertainty across different sources of product variety, it is found that:
   - When there is only one source of product variety, combination of volume uncertainty with a certain level of supply uncertainty always results in a greater increase in the average system inventory compared to combination of mix uncertainty with a certain level of supply uncertainty. For example, when there is only one source of variety (table 8.4), volume uncertainty with any level of supply uncertainty results in an increase in average inventory that ranges from 300 – 400% compared to 130 – 260% resulted by mix uncertainty.
   - However, when there are more than one sources of variety, combination of buying from global suppliers and a certain class of demand uncertainty always results in a greater increase in the average system inventory compared to combination of buying from local supplier with a certain class of demand uncertainty. Looking at table 8.5, for more than one sources of product variety, global suppliers combined with mix and volume uncertainty results in an increase in average inventory that ranges from 460 – 770% while buying from local suppliers results in an increase that ranges from 230 – 400%.
   - These findings suggest that when more types of material are required to produce different product variants, the decisions to source from local or global suppliers have more significant impact on the average inventory.

8.5.1.2 The impact of increasing level of supply uncertainty on average system inventory

In order to identify the impact of increasing supply uncertainty for any class of demand uncertainty, the relative differences between buying from local suppliers and global suppliers in a medium (table 8.6) and a high (table 8.7) number of options are determined. Both tables show that there are no interaction effects between increasing number of material options and increasing level of supply uncertainty. Under a certain type of demand uncertainty, the impact of increasing supply delivery uncertainty on average inventory with medium and high number of options is more or less the same.

Table 8.6 Impact of increasing level of supply uncertainty with medium number of options on average system inventory

Source of Product Variety	Mix Uncertainty			Volume Uncertainty		
	Local Supplier	Global Supplier	Change from Local - Global (%)	Local Supplier	Global Supplier	Change from Local - Global (%)
MM	6067	9407	55	10112	13127	30
UM	6081	9450	55	10117	13045	29
PM	6086	9537	57	10121	13138	30
MMUM	8882	15018	69	11430	17397	52
MMPM	8883	15014	69	11455	17513	53
UMPM	8896	15024	69	11517	17484	52
MMUMPM	11281	20001	77	12809	21882	71

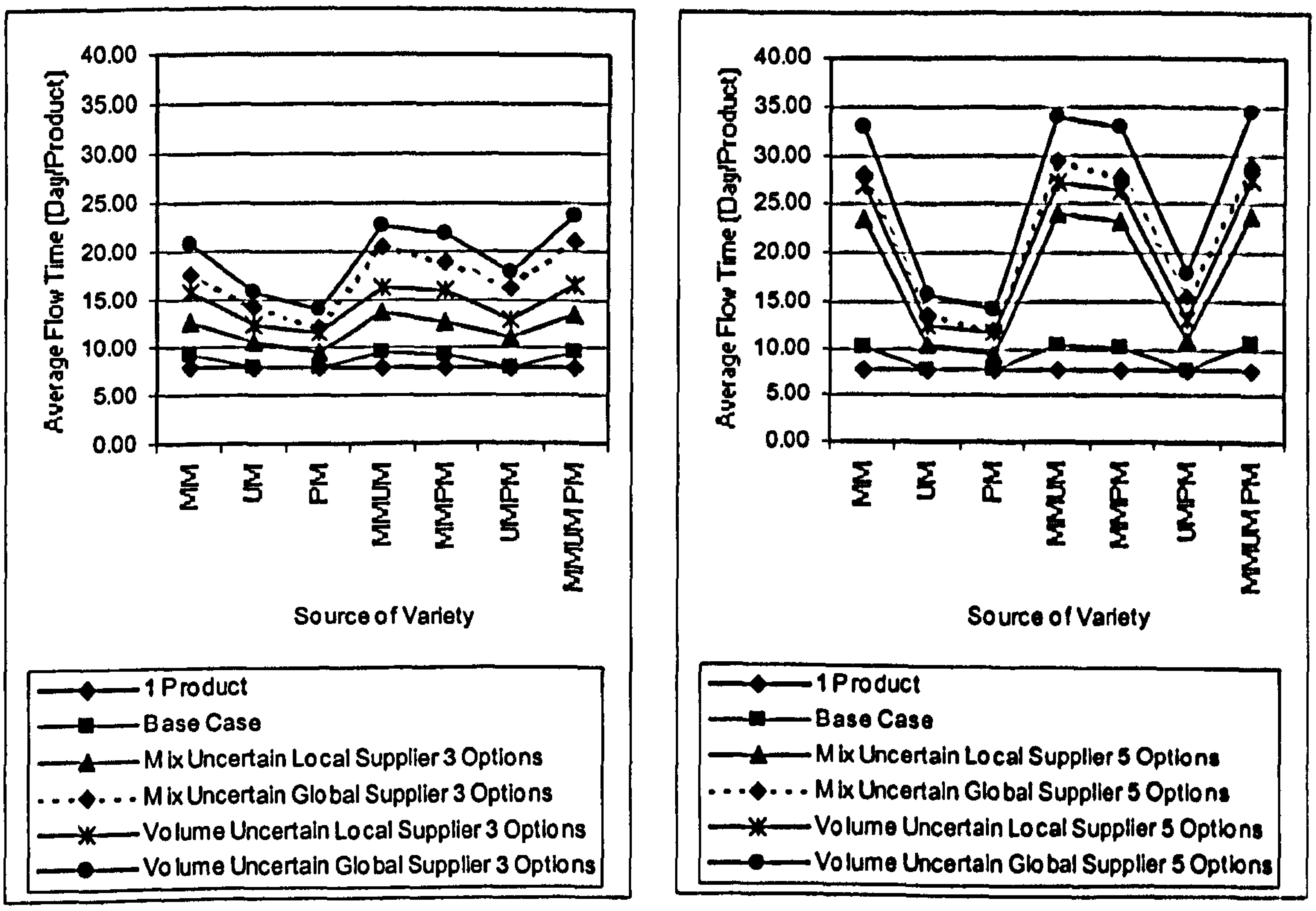
Table 8.7 Impact of increasing level of supply uncertainty with high number of options on average system inventory

Source of Product Variety	Mix Uncertainty			Volume Uncertainty		
	Local Supplier	Global Supplier	Change from Local - Global (%)	Local Supplier	Global Supplier	Change from Local - Global (%)
MM	5962	9248	55	10223	13262	30
UM	5982	9252	55	10225	13184	29
PM	5960	9241	55	10204	13147	29
MMUM	8532	14430	69	11614	17568	51
MMPM	8533	14367	68	11653	17726	52
UMPM	8522	14380	69	11587	17506	51
MMUMPM	10579	18865	78	13055	22100	69

Stronger interaction effects are found between different levels of supply uncertainty and different classes of demand uncertainty. The impact of increasing supply uncertainty on average system inventory is greater in uncertain mix situations compared to uncertain volume situation. For both three and five options, increasing supply uncertainty in uncertain mix situation results in an increase in average system inventory, which ranges from 55% - 78% compared to an increase in the range of 29 – 71% under uncertain volume situation. This means that changing the suppliers from local to global will have more damaging interaction effect on average system inventory under mix uncertainty compared to volume uncertainty situations.

8.5.2 The impact of increasing product variety, supply uncertainty and demand uncertainty on average flow time

The impacts of different levels of supply uncertainty and different classes of demand uncertainty on average flow time when the number of material options is three and five are presented in figures 8.2.a and 8.2.b, respectively. Disruptions caused by supply and demand uncertainty also affect the performance of the supply chain in terms of average flow time. Supply delivery uncertainty leads to occurrences of lateness in material delivery. Demand uncertainty means that when forecasts underestimate the actual demand, some materials are not available in the right amount. Both of these situations cause delays in the production of certain batches and eventually lead to longer average flow times. As shown in figures 8.2.a and 8.2.b, every combination of supply uncertainty and demand uncertainty with a medium and a high number of options results in longer average flow times relative to the base case.



(a) (b)

Figure 8.2 The impact of supply and demand uncertainty on average flow time in medium number of options (a) and high number of options (b)

8.5.2.1 The impact of supply and demand uncertainty on average flow time relative to base case

Tables 8.8 and 8.9 present the impact of different combinations of supply uncertainty and demand uncertainty with medium and high number of options on the average flow time in more detail. Clearly, the evident shows that volume uncertainty has relatively greater impact on average flow time compared to mix uncertainty for a certain level of supply uncertainty and a certain number of material options.

For example, when the number of main material options is three and main materials are bought from a local supplier (table 8.8), volume uncertainty results in a 71% increase in the average flow time while mix uncertainty only results in a 36% increase in the average flow time.

As expected, buying from global suppliers with greater supply uncertainty compared to local suppliers always results in longer average flow time for a certain class of demand uncertainty in either three or five material options. As shown in table 8.8, for a medium number of options, buying materials from global suppliers results in increases in the average flow time, which range from 56-122% and 81-151% when mix and volume is uncertain, respectively. For the same number of options, buying from local suppliers results in increases that range only 23 – 45% and 50 – 77% under uncertain mix and volume, respectively.

Table 8.8 Impacts of supply and demand uncertainty in medium variety situations on average flow time relative to base cases

Source of Product Variety	Base Case	Mix Uncert. & Local Supplier	Change from Base Case (%)	Mix Uncer. & Global Supplier	Change from Base Case (%)	Volume Uncer. & Local Supplier	Change from Base Case (%)	Volume Uncer. & Global Supplier	Change from Base Case (%)
MM	9.28	12.61	36	17.65	90	15.92	71	20.70	123
UM	7.82	10.63	36	14.09	80	12.39	58	15.81	102
PM	7.79	9.55	23	12.18	56	11.65	50	14.05	81
MMUM	9.44	13.71	45	20.54	118	16.38	74	22.61	140
MMPM	9.31	12.65	36	18.99	104	16.08	73	21.92	135
UMPM	7.86	11.17	42	16.28	107	12.80	63	17.79	126
MMUMPM	9.44	13.52	43	21.00	122	16.71	77	23.74	151

Table 8.9 Impacts of supply and demand uncertainty in high variety situations on average flow time relative to base cases

Source of Product Variety	Base Case	Mix Uncert. & Local Supplier	Change from Base Case (%)	Mix Uncer. & Global Supplier	Change from Base Case (%)	Volume Uncer. & Local Supplier	Change from Base Case (%)	Volume Uncer. & Global Supplier	Change from Base Case (%)
MM	10.03	23.43	134	27.94	179	26.86	168	32.90	228
UM	7.83	10.52	34	13.59	73	12.66	62	15.66	100
PM	7.78	9.45	21	12.06	55	11.74	51	14.09	81
MMUM	10.49	23.94	128	29.20	178	27.12	159	33.84	223
MMPM	10.04	23.16	131	27.77	177	26.37	163	32.73	226
UMPM	7.85	10.92	39	15.53	98	13.03	66	17.76	126
MMUMPM	10.55	23.66	124	28.80	173	27.40	160	34.31	225

Similar trends are found when the number of options is changed to five. The only difference is that the impact of main material is much greater than when the number of options is three. For a high number of options, buying from global suppliers resulted in increases on the average flow time that range from 55 – 178% and 81 – 228% under uncertain mix and volume, respectively. Buying from local suppliers only resulted in increases in average flow time that range from 21 – 134% and 51 – 168% for the same situation (Table 8.9).

These results highlight the interaction effects that exist among different sources of product variety, different number of options, supply uncertainty and demand uncertainty. Changing the number of main material options under uncertain demand and supply amplifies the different impacts caused by different sources of product variety. For every combination of supply and demand uncertainty investigated in this set of experiments, only increasing the number of options for the main material consistently results in longer average flow time.

Increasing the number of options for unique or packaging material does not have a significant impact on the average flow time. Under every combination of demand and supply uncertainty, the impacts caused by unique and packaging material variety on average flow time when the number of options is three and five are relatively the same. For example, when material is bought from local suppliers under uncertain mix situations, unique material variety results in 36% and 34% increases in the average flow time when the number of options is three and five, respectively. The results also indicate that increasing supply uncertainty has a greater impact on average flow time compared to the impact of different classes of demand uncertainty.

8.5.2.2 The impact of increasing level of supply uncertainty on average flow time

Uncertainty associated with aggregate-level or product-level demand might be more difficult to control compared to changing the level of supply uncertainty. Therefore, the impact of increasing supply uncertainty on average flow time for any class of demand uncertainty is calculated. The results are presented in tables 8.10 and 8.11 for the case with medium and high variety, respectively.

Table 8.10 Impacts of increasing the level of supply uncertainty with medium variety on average flow time

Source of Product Variety	Mix Uncertainty			Volume Uncertainty		
	Local Supplier	Global Supplier	Change from Local - Global (%)	Local Supplier	Global Supplier	Change from Local - Global (%)
MM	12.61	17.65	40	15.92	20.70	30
UM	10.63	14.09	33	12.39	15.81	28
PM	9.55	12.18	28	11.65	14.05	21
MMUM	13.71	20.54	50	16.38	22.61	38
MMPM	12.65	18.99	50	16.08	21.92	36
UMPM	11.17	16.28	46	12.80	17.79	39
MMUMPM	13.52	21.00	55	16.71	23.74	42

Table 8.11 Impacts of increasing the level of supply uncertainty with high variety on average flow time

Source of Product Variety	Mix Uncertainty			Volume Uncertainty		
	Local Supplier	Global Supplier	Change from Local - Global (%)	Local Supplier	Global Supplier	Change from Local - Global (%)
MM	23.43	27.94	19	26.86	32.90	22
UM	10.52	13.59	29	12.66	15.66	24
PM	9.45	12.06	28	11.74	14.09	20
MMUM	23.94	29.20	22	27.12	33.84	25
MMPM	23.16	27.77	20	26.37	32.73	24
UMPM	10.92	15.53	42	13.03	17.76	36
MMUMPM	23.66	28.80	22	27.40	34.31	25

When the number of options is three, increasing the level of supply uncertainty has a greater impact on average flow time under mix uncertainty compared to volume uncertainty for every source of product variety. Changing the suppliers of different types of material from local to global results in an increase that ranges from 28 – 55% under uncertain mix situation compared to only 21 – 42% under uncertain volume situation. This means, for a medium level of variety, increasing the level of supply uncertainty will amplify the impact of mix uncertainty more than the impact of volume uncertainty for every source of product variety. This is because:

- In medium variety and mix uncertain situations, the impact of forecast error is limited only to material that is the source of product variety. Thus, higher supply delivery uncertainty for materials that are the source of product variety will cause a significant increase relative to the situation with lower supply delivery uncertainty.
- In medium variety and volume uncertain situation the forecast error affects the requirement of all materials. This means that the production can be delayed by lateness and shortages of material. Thus, even in a lower supply delivery uncertainty situation, the average flow time is relatively long. The influence of volume uncertainty on the average flow time appears to lessen the individual impact of supply uncertainty.

When the number of options is five, the interaction effect of increasing the level of supply uncertainty with different types of demand uncertainty varies across different sources of product variety. When unique and packaging materials are the sources of product variety, increasing the supply uncertainty has a greater impact under uncertain mix compared to uncertain volume situation. However, when the main material is the source of variety, increasing the level of supply uncertainty has a greater impact under uncertain volume compared to uncertain mix situation. For example, when the main material is the source of product variety, changing from local to global suppliers under uncertain mix only resulted in a 19% increase in the average flow time. However, increasing the level of supply uncertainty under uncertain volume situation resulted in a 22% increase in the average flow time.

This indicates that the impact of main material variety is magnified by a high number of options, volume uncertainty and high supply delivery uncertainty. The significant increase in average flow time is caused by set-up time, delays due to shortages and lateness of main material. Because main material is required at the beginning of the production, this extended lead-time affects the production of subsequent batches leading to extensive queue time and some production has to be carried over to the following month (backlog).

8.6 Worst case analysis

Results from the experiment presented in this chapter provide insights on the impact of product variety, demand and supply uncertainty on the average performance of international supply chains. It is clear that producing high variety under uncertain demand and supply lead-time results in damaging impact on the supply chain performance. To provide insights on the extreme impacts of high product variety and high uncertainty on the **variability** of the performance measures, additional analysis referred as **Worst Case Analysis** is conducted. Results from the worst case analysis highlight that producing high variety under uncertain demand and supply introduces great risks to the supply chain as: 1) the maximum level of inventory that they have to carry could be very high and 2) the flow time to satisfy demand could be very long. More detailed description of the worst-case analysis can be found in **Appendix 8.**

8.7 General and practical implications

8.7.1 General implications

Several important findings can be concluded from these sets of experiments:

1. *The impact of global suppliers*: buying from global suppliers that have greater supply delivery uncertainty always results in more damaging impacts on both average system inventory and average flow time compared to buying from local suppliers for every class of demand uncertainty with any number of material options. For example, in maximum variety situation, buying from global suppliers under uncertain volume situation results in an increase in average inventory in the order of over 700% compared to only 400% if the materials are bought from local suppliers.
2. *The impact of aggregate-level demand uncertainty*: based on the parameters used in this set of experiments, uncertainty in aggregate-level demand has a relatively more damaging impact on both average system inventory and average flow time compared to uncertainty in product-level demand for the two levels of supply uncertainty and every number of material options. In a maximum variety situation and materials are bought from global suppliers, aggregate-level uncertainty results in over 200% increase in average flow time compared to only 120% increase resulted by product-level uncertainty.

3. *The impact of number of material option*: increasing the number of material options with any combination of supply and demand uncertainty has a different impact on average system inventory and average flow time:
   - Increasing the number of material options does not have significant impact on average system inventory.
   - Increasing the number of main material options consistently results in a damaging impact on average flow time for any combination of supply and demand uncertainty. Increasing the number of unique or packaging material options has no significant impact on the average flow time.
4. *The combined impact of demand and supply uncertainty*: comparing the impact of different combinations of demand and supply uncertainty indicates that:
   - In terms of average inventory, the impact of a certain combination of demand and supply uncertainty appears to be affected by the source(s) of variety. When different types of material are combined to produce different product variants, the decisions to source from local or global suppliers have a more significant impact on the average inventory.
   - In terms of average flow time, for any source or combination of sources of product variety, buying from global suppliers combined with any class of demand uncertainty always results in greater impact on the average flow time compared to combination of buying from local suppliers with any class of demand uncertainty. For a high number of material options, buying from global suppliers results in an increase in average flow time that ranges from 80 – 220% under

uncertain volume situation, while buying from local suppliers only results in an increase that ranges from 50 – 160%.

5. Looking at the interaction effect among different sources of product variety, demand uncertainty and increasing supply uncertainty, several points can be asserted:
   - Increasing supply uncertainty that is entailed in the policy to change the suppliers from local to global will have a more damaging impact on average system inventory if combined with mix uncertainty compared to volume uncertainty. For any number of material options, increasing level of supply uncertainty under mix uncertainty results in an increase in average system inventory that ranges from 50 – 80%, compared to only 30 – 70% under volume uncertainty.
   - In terms of average flow time, the interaction effect of increasing supply uncertainty with a certain class of demand uncertainty depends on the source of product variety.
   - When main material is the source of product variety and the number of options is three, increasing supply uncertainty will have a more damaging impact on average flow time when combined with mix uncertainty. When the number of main materials is five, increasing supply uncertainty will have more impact when combined with volume uncertainty.
   - When unique and packaging materials are the sources of product variety, increasing the level of supply uncertainty always has a greater interaction effect when combined with mix uncertainty.

8.7.2 Practical implications

8.7.2.1 Further discussion on important findings

The experimental results indicate that managing product variety in uncertain supply and demand situations clearly is a challenging task. When companies produce different products from different types of materials and both supply and demand are subject to uncertainty, the average system inventory held in stock tends to increase as:

- Some materials are delivered early and;
- Overestimation of actual demand means that the materials have to be held in stock longer than necessary.

Furthermore, lateness in material delivery and underestimation of actual demand leads to delays in the production of certain batches that eventually extends the average flow time.

There are two main findings worth discussing further. First, findings from the experiments show that uncertainty associated with aggregate-level demand (volume uncertainty) appears to be more pernicious than uncertainty in product-level demand (mix uncertainty). However, when mix uncertainty is combined with increasing supply delivery uncertainty i.e. buying from global suppliers, the potential interaction effects are pernicious. In some situations, changing the suppliers under mix uncertainty might results in almost the same impact as volume uncertainty. For example, when the number of unique options is three, changing the supplier from local to global under uncertain mix situation results in a 30% increase in average flow time. This relative increase is greater than the increase resulted from changing the suppliers under uncertain volume situation (28%). This means that a combination of high supply delivery time with demand uncertainty, either at aggregate or product level, is always pernicious to the performance of supply chain. In other words, when demand is uncertain the sourcing decisions that determine supply delivery uncertainty are very significant to supply chain performance.

Another noticeable finding is associated with the level and source of product variety. The experimental results suggest that increasing the number of options of different sources of product variety might not always be damaging with respect to either average flow time or average system inventory. Increasing the number of options means that a greater number of different products has to be produced within the same facility, which eventually means more time spent for changeovers activities.

In this set of experiments, only increasing the number of main material options consistently results in longer average flow time, while increasing the number of options for unique and packaging materials does not have a significant impact on the average flow time. These results are due to the fact that in the experiments, set-up times and processing time associated with main material is far more significant than for unique and packaging materials. It can be concluded that:

- The impact associated with variety caused by materials depends on the significance of the material on the production. The earlier the materials are required for the production, the impact on supply chain operations becomes more significant.

- Producing more product variants from materials that are used at a later production stage will have a less damaging impact on supply chain operations.

This is highlighted further from the results of combining more than one sources of product variety e.g. combining main materials and unique materials as the sources of product variety. Although these situations result in a slight increase from the impact of individual source of variety, because more materials have to be procured, the increase is not significant. This means that as long as the production of different product variants can be scheduled to minimise changeover time, then the impact of increasing the level of variety across different facilities is not as pernicious as increasing the number of product variants sharing the facility at the beginning of the process.

8.7.2.2 Strategy to cope with product variety, supply and demand uncertainty

Companies producing high product variety, whilst facing demand and supply uncertainty can certainly benefit from applying various strategies related to product variety, supply uncertainty reduction and demand uncertainty reduction discussed in chapters 6 and 7. Here, we particularly assess the potential application of such strategies in the case of SHOES.

SHOES can certainly attempt to minimise the set-up associated with production of different types of shoes. However, considering that shoes are relatively simple products, SHOES might not find big incentive in applying product-based strategies such as modular design or component sharing. In fact, accessories are part of the product design that appeal to customer, so SHOES might not want to rationalise such components.

The effort to improve SHOES performance might be directed to develop what Lee (2002) referred as an agile supply chain. In the supply side, SHOES might reduce supply delivery uncertainty by minimising variation in raw or main material supply and ensuring that key materials always available in stock. At the same time, companies may mitigate the negative impact of demand uncertainty by being responsive to the market needs. This is where the challenges are greatest. Several authors have proposed that companies involved in the apparel industry could alleviate the negative impact of demand uncertainty by attempting to apply 'time compression', 'quick response' or 'accurate response' strategy (Fisher et al., 1994; Forza and Vinelli, 1997; Forza and Vinelli, 2000). These strategies require the ability to rapidly adjust production to satisfy changes in the market. However, with long-lead time in SHOES global pipeline, this might be difficult to achieve. The company might attempt to rationalise their product offering and reconfigure their international supply chain to reduce some of the negative impacts of product variety, as well as supply and demand uncertainty.

8.8 Conclusions

This chapter has investigated the impact of increasing product variety when both supply and demand are uncertain. In any class of demand uncertainty, buying from global suppliers always results in a worse impact on both performance of the supply chain compared to buying from local supplier.

Within the given set of parameters, uncertainty associated with aggregate-level demand results in longer average flow time and higher level of average system inventory compared to product-level demand uncertainty. However, if combined with high supply uncertainty, the impact of mix uncertainty is almost as pernicious as the impact of volume uncertainty. Finally, the impact associated with variety caused by materials depends on the significance of the material on the production. Variation in materials that are required early in the production and that generate longer set-up, have a more pernicious impact on supply chain operations.

Chapter 9
Framework for Managing Product Variety in International Supply Chains

The main goal of this study is to investigate the issue of product variety in the context of international supply chains management. The empirical study analyses the configuration and co-ordination characteristics of companies involved in international supply networks. It also shows how different international supply networks face different challenges in terms of product variety, as well as supply and demand uncertainty. The simulation model was developed based on relevant information gathered from the empirical study. The simulation experiments explore the impact of different combinations of factors on the performance of international supply chain. The simulation results also highlight the potential benefits of various strategies proposed in the literature to cope with the problems.

This chapter synthesises findings from both the empirical and simulation study by proposing a general framework to:

1. Understand the inter-relationships between product variety, configuration, co-ordination, supply uncertainty and demand uncertainty and understand the impact of these factors on international supply network performance.
2. Address the negative impact of such factors in order to improve the performance of international supply networks.

The first and second parts of the framework are described in sections 9.1 and 9.2, respectively. In describing the framework, we will not repeat the evidence obtained from the empirical and simulation study.

9.1 Framework to understand interrelationship across factors in managing product variety in international supply networks

The review of the literature and findings from the empirical study highlight several important factors in managing product variety in international supply networks. These factors are depicted in figure 9.1. The relationships among these factors are discussed in the following sections.

9.1.1 Factors affecting configuration of international supply networks

A company's strategic orientation is influenced by *product, industry* and *market* characteristics. A company producing functional products is likely to put more effort in achieving cost efficiency, whilst a company producing innovative product generally should attempt to achieve market responsiveness (Fisher, 1997). Companies producing intermediate or industrial products will put more emphasis on responsiveness to every customer compared to companies producing consumer goods.

The *characteristics of the industry* also influence the strategic orientation of a company. A company involved in a labour-intensive and mature industry, such as apparel, typically puts a great emphasis on keeping the labour costs down. In contrast, companies involved in a capital-intensive industry such as semiconductors may spend a large amount of investment in order to keep pace with rapid changes in the technology. Cost may be less important to such a company compared to quality and reliability. With the fast changing pace of the business environment today, there are also companies involved in many industrial sectors that put their attention on minimising risks.

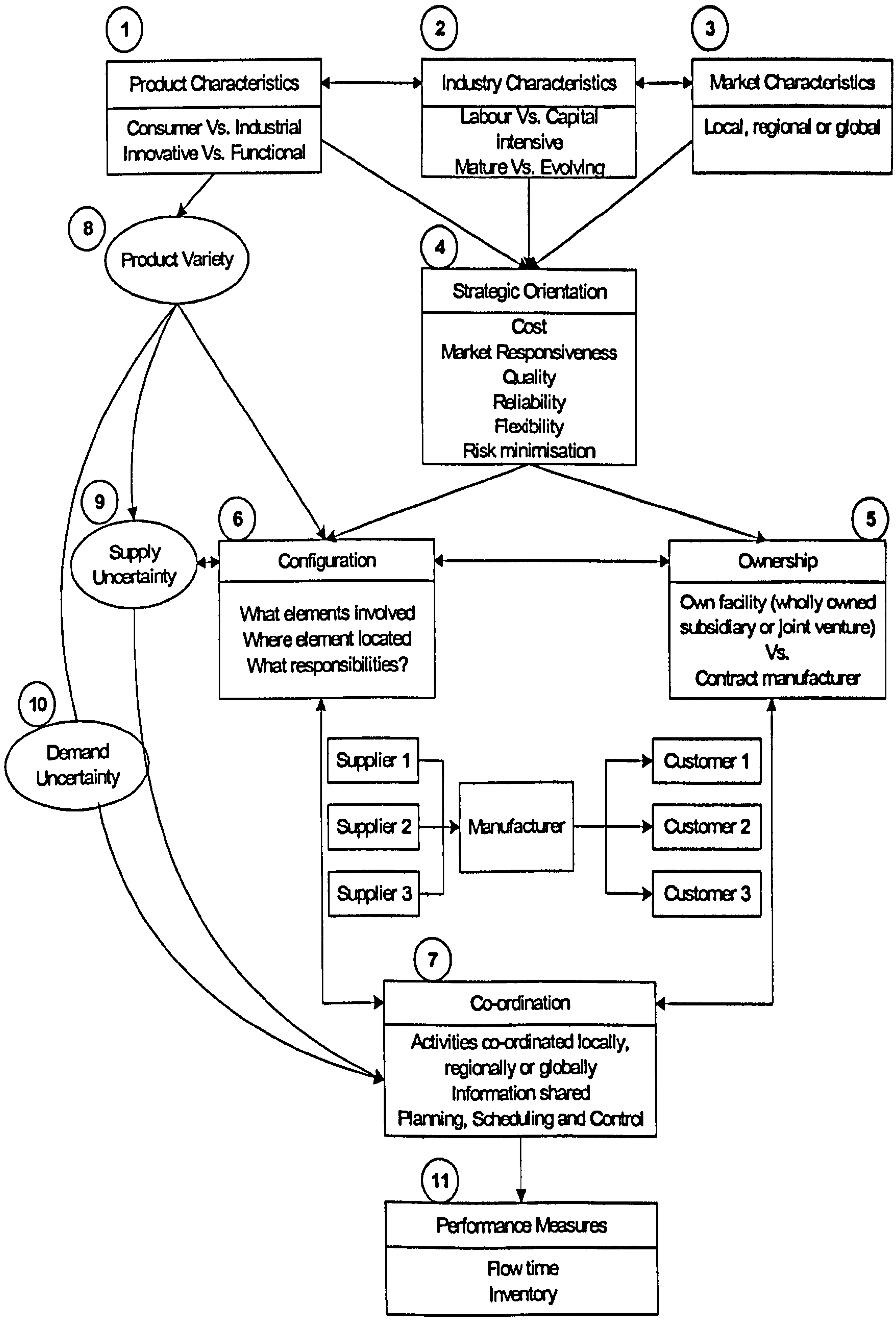


Figure 9.1 Factors and their interrelationships in managing product variety in international supply networks

A company's market coverage also relates closely to their *strategic orientation.* A company serving global markets certainly faces a great challenge to be responsive to the need of each national market. This is less of a problem for a company serving mainly a local market.

The strategic orientation of a company is an important factor determining the *configuration of international supply networks* (Ferdows, 1989; Harzing, 2000). A company attempting to achieve market responsiveness typically establishes its subsidiaries close to its main markets. One of the main goals for a company in developing global supply networks is to achieve low cost. A company focusing on delivery dependability may not prefer an international supply network configuration as it typically involves long and relatively uncertain lead-times. Similarly, a company that emphasises on quality of product may resist the idea of developing dispersed offshore supply networks as it inhibits direct control over quality. More recently, there is an increasing number of companies that develop clusters of foreign subsidiaries in different parts of the world in order to minimise the risks associated with having only one subsidiary e.g. factory shut down, strikes, etc.

9.1.2 Driving factors, strategic orientation and ownership of international supply network

Product, industry, and market characteristics as driving factors of configuration are also expected to influence the *ownership of international supply network.* Simple products, requiring relatively low development in product and process technology, are potential candidates to be outsourced to outside suppliers. On the other hand, companies that manufacture products with fast advancement in product and process technology (i.e. fast technological clockspeed according to Fine et al., 2002) have an incentive to keep the production in-house in order to protect the intellectual property rights and ensure the required quality is achieved. Finally, the availability of large, stable markets or free trade markets such as NAFTA or ASEAN may motivate the establishment of a foreign facility and ensure that it is economically justifiable.

Strategic orientation also determines a company's choice of conducting activity in its *own manufacturing unit* or *contracting out*. Companies attempting to ensure reliable delivery and quality of output may prefer to conduct the operations within their own manufacturing unit. On the other hand, a company involved in an industry such as apparel, which is characterised by a high labour content and periodic swings in demand, might attempt to achieve cost and scale flexibility through subcontracting.

9.1.3 Ownership, configuration and co-ordination

Close relationships exist between *ownership*, *configuration* and *co-ordination*. The configuration of vertically integrated MNC supply networks tends to be static over a relatively long period of time. Furthermore, considerable co-ordination efforts are found across elements in the network in order to ensure smooth running of operations.

On the other hand, with no long-term commitment between elements in the contract manufacturer supply networks, the configuration is likely to change from one period (selling season) to another. The nature of relationships between elements belonging to different organisations in a vertically disintegrated supply network is influenced by the competition i.e. availability of capable suppliers and easiness for buyers to change to different suppliers. When capable suppliers are scarce, buyers may find it more difficult and costly to change suppliers. Such buyers are more motivated to develop close relationships with their suppliers. In contrast, when there are many capable suppliers in the market, buyers may choose a supplier offering the best value at a certain time, in other words engage in short-term contract or a traditional market-oriented supply relationship.

9.1.4 Configuration and co-ordination strategy

The configuration of international supply networks is closely related to the way in which elements in the supply network have to be linked and integrated i.e. co-ordination. An international supply network consisting of autonomous subsidiaries is typically less integrated and co-ordinated. In contrast, an international supply network that separates successive activities across different elements in the international supply chain i.e. *process-based supply network* needs to be highly co-ordinated in order to ensure a smooth flow of information, materials and products across different elements in the supply network. Supply networks that allocate production of a group of products to different subsidiaries, i.e. *product-based network,* are less pressured to integrate their day-to-day operations compared to process-based supply networks.

Geographical separation between different activities in the value chain typically creates a longer lead-time. Transportation of goods across different countries, particularly by sea, is subject to great uncertainty and inflexibilities due to various factors including weather, custom delays, etc.

9.1.5 Product characteristics and product variety

Companies producing different types of product are expected to face different issues related to *product variety.* A company that produces innovative products is expected to offer higher levels of product variety compared to a company producing functional products. However, these distinctions may not fit all companies. Many companies in today's business environment introduce additional attributes to their functional product in order to differentiate their product from competitors and gain greater market share. In general, product variety affects the supply chain in two value chain activities: 1) the *procurement of materials* and 2) *the production.*

9.1.6 Product Variety, Configuration and Co-ordination

Randall and Ulrich (2001) argue that there are ways to match a company's product variety and supply chain structure. They suggest that a company that offers product variety incurring high production costs (direct materials, labour, manufacturing overhead, and process technology investment) have an incentive to aggregate production to achieve economies of scale, although it means locating production far from the market. On the other hand, when the variety offered by a company incurs high market-mediation costs (inventory, mark-down and lost sale), a company might prefer to build local plants at a cost of reduced scale.

Child et al. (1991) argue that one way to reduce co-ordination and configuration complexity is by reducing interdependencies among plants. They urge companies to dedicate plants to a type of finished product and not to a function or a process step. In other words, product-based structure reduces complexity compared to process-based structure.

9.1.7 The impact of product variety on supply chain performance

The impact of different combination of factors on supply chain performance is captured in figure 9.2.

Increasing product variety results in longer average flow time due to the need to conduct set-up activities. The impact of product variety depends on: 1) when the variety takes place (in what stages in the value chain variety occurs) and 2) the severity of set-up required to produce different types of product variety. Variety occurring early in the production or requiring long set-up is likely to have a pernicious impact on supply chain performance. Main material variation occurring early in the production process and requiring significantly long set-up time caused longer average flow time, whilst variety at the end of the production process with minor set-up time caused negligible impact on average flow time.

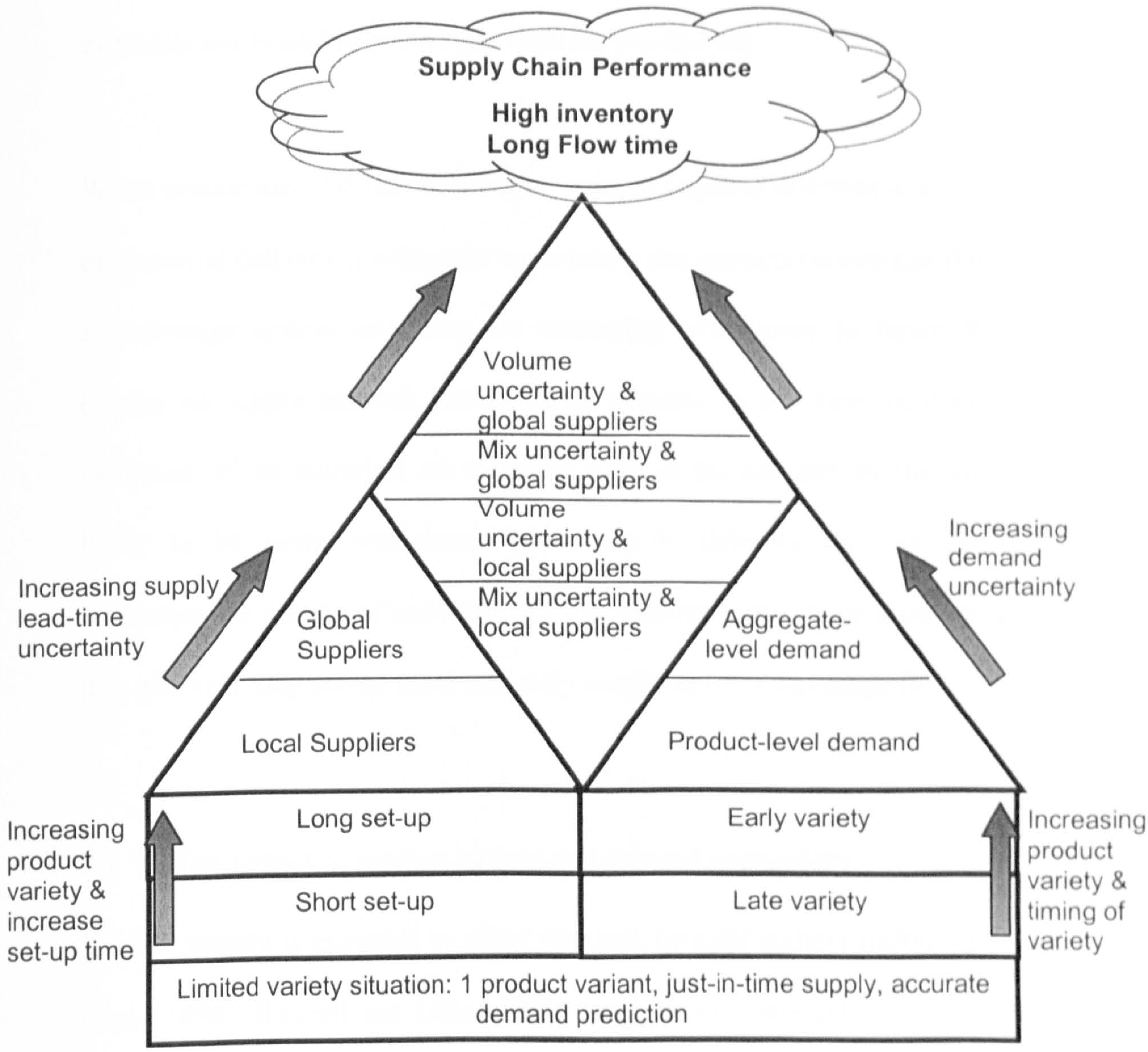


Figure 9.2 The impact of different combination of factors on international supply networks performance

9.1.8 The impact of product variety and supply uncertainty

Procurement of materials is affected by product variety, as producing different product variants typically requires different types of materials. This means that the supply network configuration may become more complex as more suppliers are involved in the supply network. A wide variety of materials also implies that more suppliers and more inventory need to be managed. As a result, more co-ordination efforts need to be dedicated to ensure that the right materials are available at the right time for production.

When production of different product variants requires different materials, and the material delivery is subject to uncertainty the impacts on average flow time and average system inventory are damaging. As shown in figure 9.2, the impact on supply network performance is worst as the level of uncertainty increases. If the materials are required early in the production, the impact is likely to be more pernicious. When supply delivery time is uncertain, increasing the variety of materials that are required early in the production and that generate long set-up times typically results in longer average flow time.

9.1.9 The impact of product variety and demand uncertainty

Product variety is expected to affect demand. Several authors including Fisher et al. (1994), Randall and Ulrich (2001) suggest that product variety makes it more difficult to predict demand, particularly at a product level. Companies producing a high variety tend to face higher uncertainty in their demand. Companies acting as contract manufacturers tend to have relatively high demand uncertainty compared to subsidiaries of MNC corporations. This is unsurprising, as most contract manufacturers have no long-term contract with any of their customers. Thus, their demand pattern is characterised by peaks and troughs depending on the availability of orders from customers.

Figure 9.2 indicates that producing high product variety when there is uncertainty on which product variant will be produced, results in increasing inventory and extending flow time. If the uncertainty affects the procurement of the entire material, typically occur if aggregate-level demand is uncertain, the impact is likely to be worse compared to uncertainty related to product-specific materials. The error in predicting the materials required early in the production leads to damaging impact on the average flow time. When demand is uncertain, increasing the variety of materials that are required early in the production and that generate long set-up times results in longer average flow time.

9.1.10 The impact of product variety, supply and demand uncertainty

When both supply and demand are subject to uncertainty, production can be delayed due to lateness of material delivery and material available is less than the actual production requirement. Inventory is likely to be higher as material can be delivered: 1) earlier than expected time and 2) greater than the actual production requirement.

Producing high variety when both delivery time and demand are subject to uncertainty increases average inventory and average flow time. As shown in figure 9.2, combination of different levels of supply delivery uncertainty and demand uncertainty, either at aggregate-level or product-level, always leads to a pernicious impact on supply chain performance. The worst situation is when the supply network produces high variety when aggregate-level demand (volume) is subject to uncertainty and all materials are bought from global suppliers.

9.2 Managing product variety in international supply network

Understanding the relationship among key factors and their potential impact on supply chain performance provides important insights on how to manage product variety in international supply chains. In this section, the management of product variety in the context of international supply network, particularly identification of strategies to mitigate the negative impacts of various factors on supply chain performance, is discussed.

9.2.1 Aligning strategic orientation, product variety and supply network configuration

The management of product variety in the context of international supply networks should begin at a strategic level through an overall value chain assessment. Many companies would not have the chance to design their network as they have acquired a legacy network over time through mergers, acquisitions and rationalisations (MacCarthy et al., 2002). Furthermore, the design of a company's value chain has traditionally been viewed as a static enterprise, the assembling of a fixed set of suppliers and distribution channels to attain and maintain competitive advantage (Fine et al., 2002). However, with the fast changing pace of today's technologies and business environment, a company real core capability is its ability to design and redesign its value chain in order to continually attain competitive advantage.

Therefore, a company should assess its value chain in order to see if the strategic orientation, level of product variety offered and the supply network configuration are in alignment. The questions to be asked are:

- What are the characteristics of the products?
- What is the company's strategic orientation?
- What variety is useful and what variety is useless?
- Does the variety generate primarily production cost or market-mediation cost?
- Is a capable supply base available close to manufacturing unit?

Any companies might find that the answers to the above questions are in conflict with each other. For example, a company may produce a high variety requiring different types of materials, but the materials have to be bought from foreign suppliers. A typical problems found by many companies is the fact that they simply produce too many product variants that are not cost-effective or profitable. Answering the above questions may force a company to identify potential areas of improvement.

9.2.2 Achieving variety through network flexibility

In some industries, companies increasingly realise the benefit of achieving wider scope (variety) without creating business complexity through the use of contract manufacturers or trading companies. Many retailers and brand owners in developed countries use networks of contract manufacturers in low cost regions to supply them with wide variety of products at a low cost. The emergence of trading companies such as Li & Fung that specialise in bringing buyer and supplier together also contributes to network flexibility. Li & Fung, a Hong Kong trading company, helps U.S. and European retailers to purchase various goods such as clothing, home furnishing, toys etc from Asian suppliers (Magretta, 1998). Li & Fung manage the entire value-adding process from developing the products with retailers, finding Asian suppliers that can meet the retailer's requirement, controlling the production to meet the retailer's specification and finally preparing the export documentation, clearing the products through customs and delivering the items to their client (Wisner et al., 2004, p. 7). This way, the retailers can offer a wide variety of products without having to deal with the management of complex supply chains.

9.2.3 Mitigating the impact of product variety, supply and demand uncertainty in international supply network

Careful consideration of strategic orientation, the value of product variety, and supply network configuration are only the initial steps in managing product variety in an international supply chain. A company should then evaluate the impact of such decisions on day-to-day operations.

There are several important factors to manage product variety in an international supply network:

1. The timing of variety and the severity of set-ups.
2. The characteristics and location of the supply base.
3. The predictability of aggregate-level and product level demand.

Several strategies can be applied to mitigate the negative impact of the above factors on supply chain performance. The strategies can be classified into:

- <u>Structural-based strategy</u> aimed at reconfiguring supply network to enable production of a wide variety of product while maintaining low supply delivery uncertainty. This strategy includes localisation of supply base, pooling resources (inventory) to reduce risk of disruption, strategically-placed buffer and postponement.

- Product-based strategy aims to develop product design that allows production of a wide variety of products without increasing part complexity. This includes component sharing, standardisation and modularisation.
- Process-based strategy aims to develop flexible processes that enable production of a wide variety of product with negligible disruption on manufacturing. This strategy includes flexible manufacturing system and set-up time reduction.
- Co-ordination-based strategy can be employed to develop an operating policy or joint agreement with trading partners to ensure smooth running of operations. This might include applying service level agreements, penalty costs, safety stocks or strategically-placed buffer to ensure that the right materials are available at the right time for production. It also encompasses the establishment of a frozen period or time fence agreement to protect production from demand changes.
- Responsiveness strategy can mitigate the negative impact of variety, demand and supply uncertainty by being responsive to the market. This can be achieved with the support of all the above strategies. A company involved in apparel industry, for example, can produce just a small sample of product, launch it to the market and adjust production based on early market signals.

A company has to evaluate the challenges in its operation in terms of product variety, demand and supply uncertainty and carefully choose the most plausible strategies to mitigate the negative impacts of the challenges on their performance. The second part of the framework summarising the important aspects, potential impact on performance and strategy to reduce the negative impacts of product variety is presented in figure 9.3.

If variety occurs early in the value chain process, company may benefit from the use of a postponement strategy. Furthermore, when variety requires long set-ups, then product-based and process-based strategies enable them to produce a wide variety of product whilst minimising the impact of changeover time. A company facing high delivery uncertainty due to a geographically distant supplier should attempt to localise the supply base of some of the materials. They can also increase safety stocks and co-ordinate agreements to ensure that material is available for production at the right time. Another strategy that becoming common practice in some international supply chains to cope with supply delivery uncertainty is to strategically place buffer after the most uncertain part of the value chain. For example, a company in the UK that source from the Far East may place buffer at the port of entry and demand the suppliers to keep a minimum level of inventory at this point. A company facing demand uncertainty may benefit from implementation of a frozen period and time fence to prevent disruption in production due to demand changes. For uncertainty affecting mainly procurement of product-specific materials, a company may stock standard materials and buy product-specific materials just in time. Finally, they may adopt responsiveness techniques to cope with changes in the market or customer's preferences.

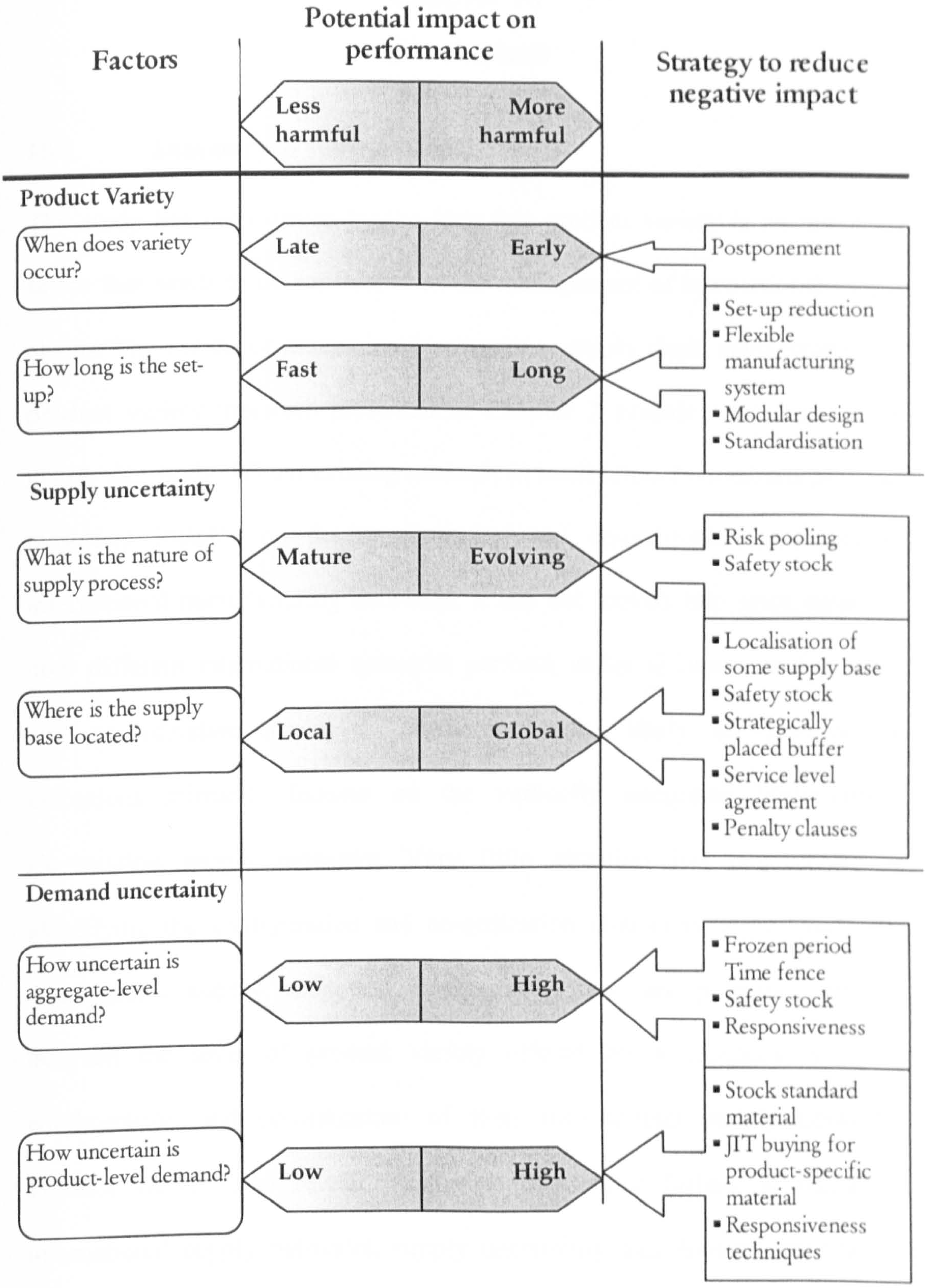


Figure 9.3 Factors and strategy in managing product variety in international supply network

Chapter 10
Conclusions

10.1 Summary of contributions

The study has been driven by the idea that product variety is an important factor that needs to be considered in the management of international supply chains. The review of international operations, supply chain management and product variety literature presented in Chapter 2 reveals several gaps that justify this study. Whilst existing research in international operations provides important insights on the configuration and co-ordination strategies of international manufacturing networks, it has not looked into great detail on how different international networks perform under different configuration and co-ordination strategies. Furthermore, the study on international operations primarily focuses on the vertically integrated Multinational Corporation supply networks. Very little attention has been given in identifying the configuration and co-ordination characteristics of vertically disintegrated supply networks. Furthermore, there are potential relations between the level of product variety offered by a company with the configuration and co-ordination of their international supply networks. Product variety also relates closely to two other factors in managing international supply networks, supply uncertainty and demand uncertainty. Therefore, it is important to study the interrelationship between product variety and other factors including configuration, co-ordination, supply uncertainty and demand uncertainty, and understand their impact on international supply chains performance.

Based on the above background, this study has provided contributions in the following ways:

1. Presenting case study evidence on the configuration and co-ordination strategies from real international supply networks with different types of ownership. The research literature is limited on such evidence.
2. Investigating the issue of product variety with other key factors commonly found in managing international supply chains, namely configuration, co-ordination, supply uncertainty and demand uncertainty through empirical study. The research literature does not currently address this issue.
3. Developing a simulation model that represents specific and important configurations and co-ordination policies of international supply networks and that enables investigation of three dominant factors: product variety, supply and demand uncertainty. There have not been many simulation studies for international supply networks reported in the literature.
4. Demonstrating and quantifying the potential impact of product variety, supply uncertainty and demand uncertainty for two primary performance metrics, namely flow time and level of inventory.
5. Proposing a framework to understand the problem of managing product variety in international supply networks and identifying potential strategies to address the problems.

10.2 Summary of findings

The empirical study and simulation study have provided important insights on the issue of managing product variety in international supply networks. These findings are summarised in this section.

10.2.1 Evidence from the empirical study

Important findings from the empirical study are summarised in this section.

10.2.1.1 Configuration and co-ordination strategies of MNC supply networks

The configuration of Multinational Corporations (MNC) supply network is affected by product, industry and market characteristics. Companies producing intermediate or industrial products, heat exchanger or chemicals, *have autonomous subsidiaries* with less integration in day-to-day operations.

International supply networks producing consumer products including shoes, light bulbs, and consumer food have different strategies in configuring their value chain activities. The light bulb and consumer food supply networks *develop 'clusters' of foreign subsidiaries* in Asia Pacific Region in order to:

- Allow the network to offer wider range of products to the market.
- Give the network the flexibility to switch the production across subsidiaries in various circumstances such as factory breakdown, strikes, political and social problems, etc.

Co-ordination activities that took place in this network configuration include export and importing finished goods, as well as sharing capacity and demand information.

One of the MNC supply networks applies a *purely global supply network*, locating each value chain activities in a certain location to capitalise on location-specific advantages, and co-ordinating all the activities globally. This international supply network is tightly co-ordinated and supported with advanced information and communication technology to ensure smooth flow of information across the elements in the supply network.

10.2.1.2 The use of foreign suppliers in MNC supply network

MNC supply networks primarily use foreign supply bases to supply materials for their dispersed manufacturing units. This is one of the main challenges facing the international supply network management, as buying from global suppliers take a relatively longer procurement time and entails higher delivery uncertainty due to shipment, weather, customs and duty problems.

10.2.1.3 Configuration and co-ordination strategies of contract manufacturer supply network

The contract manufacturers involved in the empirical study produce less sophisticated products and the production generally is labour-intensive with slow advancement in product and process technology. The contract manufacturers are involved in industries characterised by high uncertainty in demand and market preferences. The main strategic orientation for foreign buyers to use the contract manufacturer appears to be achieving low cost and flexibility in terms of scale and scope. Elements in the contract manufacturer supply networks are likely to change from one selling period to another. Limited information sharing and co-ordination efforts are evident in this type of supply networks.

10.2.1.4 Configuration and co-ordination strategies of MNC supply networks vs. contract manufacturer supply networks

Different configuration and co-ordination strategies are evident between international supply networks belonging to MNC Corporation and contract manufacturers. The configuration of MNC supply networks is relatively static over a long period of time. More co-ordination efforts are found among elements in the MNC supply network. With no long-term commitment between elements in the contract manufacturer supply network, the configuration of the supply network changes dynamically over time.

10.2.1.5 Configuration and co-ordination of MNC owning subsidiaries and contracting out

Investigation of an international supply network that owns several foreign manufacturing facilities as well as using contract manufacturers to produce some of their products support the above findings. The INTIMATE_WEAR case shows that:

- The company maintains some of the production in their own manufacturing unit to ensure delivery reliability and to be responsive to changes in customer needs.
- The company attempts to achieve cost, scale and scope advantages from their contract manufacturer.
- Intense co-ordination efforts are found in this supply network.

10.2.1.6 Nature of relationship between supplier and buyer in vertically disintegrated supply network

The nature of relationships between contract manufacturer and foreign buyers is determined mainly by the competition in terms of the availability of capable suppliers and easiness to change suppliers.

10.2.1.7 Product variety

Companies involved in the empirical study face different problems related to product variety. Different types of product have different factors that generate product variety. Some factors have greater impact on the operations compared to other factors. Unsurprisingly, most case companies indicate that product variety affects the production as it gives rise to the need for set-up activities. Furthermore, most case companies highlight that product variety affects the procurement of materials. Producing variety in most of the cases requires different types of materials in terms of raw material, components, parts, or packaging materials.

10.2.2 Evidence from the simulation study

10.2.2.1 The impact of increasing product variety

The impact of product variety depends on when the variety occurs in the value chain process and the severity of set-up to produce different products. The impact of variety occurring early in the production or requiring long set-ups is more pernicious than the impact of variety arising at a later stage of production and requiring minor set-up. Results from the simulation experiments show that main material variety that occurs early in the production and that generates long set-up results in an increase in average flow time *in the order of 30%* relative to the situation when the supply chain only produces one product. Packaging material variety that occurs at the last stage of production and requires minor set-ups has a negligible impact on average flow time.

10.2.2.2 The impact of product variety and supply uncertainty

Producing higher levels of variety means that more materials need to be procured and more inventories need to be managed. When the delivery of materials required for production is subject to uncertainty, materials might not be available at the right time for production.

Results from the simulation experiments show that producing high variety when supply delivery time of materials is uncertain increases average flow time and average inventory. The performance worsens if the materials are bought from global suppliers with a high delivery uncertainty. Increasing variety in main material, when such materials are bought from global suppliers, results *in over 160%* increase in average system inventory *and 50% increase* in average flow time, relative to constant demand and supply situation i.e. the base case.

10.2.2.3 The impact of product variety and demand uncertainty

Product variety has a close relationship with demand uncertainty. Predicting the volume and type of product that is going to sell is difficult when there is a high number of product variants. The empirical study found that companies offering higher variety face greater uncertainty in their demand. When production of different product variants requires different materials, the error in predicting demand means that the right amount of materials might not be available when needed.

Results from the simulation experiments show that producing high variety when there are errors in predicting the demand increases average flow time and average inventory. The impact on performance is more pernicious when the error affects the procurement of all materials as opposed to error that affects only procurement of product-specific materials. Increasing variety in material that is required early in the production and requires long set-up, when aggregate-level demand is subject to uncertainty, increases the average inventory and average flow time in the order of *over 250% and 140%*, respectively, relative to the base case.

10.2.2.4 The impact of product variety, supply and demand uncertainty

Producing high variety when supply delivery and demand are subject to uncertainty increases average flow time and average inventory. In this situation, the decision to choose between global and local suppliers, which affect the supply delivery uncertainty, becomes very important.

Different levels of supply delivery uncertainty combined with demand uncertainty, either at aggregate-level or product-level, results in increasing average inventory *in the order of over 100%* relative to the base case. When demand and supply are uncertain, increasing the number of main materials, from one to five results in *over 100%* increase in the average flow time relative to the base case. In the worst situation, when the system produces maximum level of variety, aggregate-level demand is subject to uncertainty and materials are bought from global suppliers, the average inventory and average flow time increase *in the order of over 700% and 200%*, respectively, relative to the base case.

10.2.3 Framework to manage product variety in international supply networks

Findings from the empirical and simulation study are synthesised to develop a generic framework to understand and manage product variety in international supply networks. The framework describes the interrelationships across key factors and potential impact of such factors on supply chain performance. Such understanding can be used to identify combination of strategies - product-based, process-based, co-ordination-based and responsiveness strategies - to mitigate the negative impact of these factors on supply chain performance.

10.3 Directions for future studies

This study presents new insights to address the issue of product variety in the context of international supply network management. However, as with all research there are a number of limitations that justify further work. Firstly, the empirical findings presented in chapter 3 mainly capture the perspective of subsidiaries in international supply networks. Empirical study that gathers evidence from various elements in the supply networks including corporate headquarters and subsidiaries would provide a more integrated view on the configuration and co-ordination issues. Evidence from different types of industry will also be beneficial to validate and add more details to the framework developed in chapter 9.

As the study covers a relatively new topic area, it focuses on bringing together several important factors and exploring relationships among these factors in managing international supply network. Thus, in conducting the simulation study, the main goal is to describe inter-relations among factors and the impact on supply chain performances. More extensive studies could be to investigate a wider range of factors than those that have been used in the simulation study. To obtain a clearer and more exact picture on the effect of individual factors, more levels could be investigated in each factor. For example, in the simulation experiments conducted in chapters 7 and 8, the aggregate-level demand uncertainty is represented by a 20% forecast error. Certainly it would be beneficial to investigate the impact of different degrees of forecast error on the supply chain performance. Similarly, more investigations are needed on the effects of other experimental factors, including more levels of product variety, mix uncertainty and supply delivery uncertainty. It is also interesting to see the impact of varying some of the input parameters used in this study including set-up time, processing time and batch size on supply chain performance.

Further study relaxing some of the assumptions in the current study would also be beneficial. The simulation study assumes that the system works without safety stock of either material or finished goods. Incorporating some of the well-established inventory policies into the simulation model might provide important insights on the behaviour of international supply networks.

In this study, the international dimension captured is limited to the geographical separation between supplier and manufacturer. Incorporating the distance between manufacturer and the market or customer or other risks inherent in international supply chain operations will provide a more comprehensive view of an international supply network.

In investigating the potential impact of mix uncertainty, we use a mechanism that generates product-level demand as a proportion of aggregate-level demand. Further studies might develop different mechanisms to generate product-level demand uncertainty e.g. product-level demand is generated independently from aggregate-level demand.

Finally, investigation on the behaviour of vertically disintegrated international supply networks is certainly an important agenda for future studies. The empirical study has obtained several important characteristics of international supply networks consisting of contract manufacturers. Developing a simulation study that captures: 1) the dynamic behaviour of contract manufacturer including periodical swings in demand or even lumpy demand, 2) transactional cost associated with managing contract manufacturer certainly promises fruitful findings. It would enable comparison on the benefit and costs associated with allocating production in their own manufacturing units as opposed to contracting to outside suppliers.

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APPENDIX 1 SEMI-STRUCTURED INTERVIEW QUESTIONS

1. **General business characteristics**
   1.1. What is the company's status of ownership?
   1.2. Who are the company's main customers?

2. **Product and market**
   2.1. What types of product does the company produce (General product description)? Does your product satisfy individual or industrial customer?
   2.2. Please describe your product architecture?
      2.2.1. What are the parts that make up the product?
      2.2.2. How do you classify your product? On what bases?
      2.2.3. What are the main product lines?
   2.3. What is the typical selling cycle (if any)?
   2.4. What is the (average) expected life cycle of the product?
   2.5. How many product lines/types do the company produce in one cycle?
   2.6. Where is the market?
      2.6.1. What is the percentage of the product sold locally?
      2.6.2. What is the percentage of the product sold in foreign market (what country)?
   2.7. Do the company produce standard products for different markets?
      2.7.1. How to handle specific markets' preferences?

3. **Value chain activities**
   3.1. What are the elements that constitute the international value chains?
   3.2. Where is each element located?
   3.3. Demand management
      3.3.1. Please explain the typical demand management process?
      3.3.2. What element is responsible for this process?
      3.3.3. What trigger the production (forecast/order)?
   3.4. Planning
      3.4.1. Who conduct the production planning? How does information from demand management transferred to planning (if conducted by different parties)?
      3.4.2. What are the typical planning horizons?
      3.4.3. How are productions allocated to production sites? What factors need to be considered? What are the typical rules (capacity/competency/product/process/regional based)?
      3.4.4. How often do you receive order in a year? Can you create a pattern of your incoming order?
      3.4.5. What is the typical production cycle?
      3.4.6. Can you put a proportion to the production of each type of product?
      3.4.7. How often does this proportion change?
      3.4.8. What do you do when there are changes in initial order (re-schedule)?
   3.5. Production

3.5.1. What is the average production capacity?
3.5.2. Who is responsible for scheduling of production? How docs information from planner transferred to production (if conducted by different parties)?
3.5.3. What is the typical rule (first come first out/priorities)?
3.5.4. What are the stages of production?
3.5.5. Where does each stage take place and who is responsible for it?
3.5.6. Which stages are automated and which are manual (percentage)?
3.5.7. Are productions of different types of products conducted in the same production line (worker)?
3.5.8. What activities need to be done when changing from one types of product to another? How long do these activities take?

3.6. Product design and development
3.6.1. Who is responsible for product development activities?
3.6.2. How often do they conduct product development? Is it typically improvement of past products or is it completely new (percentage)?

3.7. Procurement of material
3.7.1. What are the main materials needed for production?
3.7.2. Do you have standard materials (that you always use for every product) or product-specific materials?
3.7.3. Where do you buy it?
3.7.4. Where are the main suppliers? Do you have specific suppliers for every material or you just buy from supplier that best meet your criteria in the market?
3.7.5. What is the average lead-time to procure the material (including transportation)?
3.7.6. What is the means of transportation for materials (ship, air?)
3.7.7. Are you facing uncertainties in material delivery time?
3.7.8. What are the policies for raw materials?
3.7.8.1. Is it standard for each production sites?
3.7.8.2. Where is the stock of raw materials being held? How is it transported to production sites?
3.7.8.3. Are there different policies for standard and unique materials?

3.8. Quality control
3.8.1. Who is responsible?
3.8.2. In general do the company face a lot of quality problems? Do international operations add to the QC problem?
3.8.3. Does different site have different standard of quality?

3.9. Distribution, sales and marketing
3.9.1. Does the company sell directly to end-user? If not, who is responsible for that?
3.9.2. What is the common distribution channel?
3.9.3. What are the means of transportation?
3.9.4. How long does it usually take?

4. Co-ordination (Communication & Information Flow)

4.1. Link/Integration & co-ordination mechanism

4.1.1. What are the activities that you need to co-ordinate with other element in the supply network? What activities need to be co-ordinated locally, regionally or globally (centralisation)?
4.1.2. Which of the following co-ordination mechanism employed among elements in the supply network?
4.1.2.1. Direct supervision
4.1.2.2. Formalisation (standardisation) of process?
4.1.2.3. Output control
4.1.2.4. Informal co-ordinations (informal communication)

4.2. Nature of relationships
4.2.1. How do you choose to engage with other element? Is it transactional market relationships (whoever is in the market and satisfy your criteria) or are you working closely with (some) other elements in the supply chain?
4.2.2. Do you have any of these below in your relationships with other elements of the supply chain?
4.2.2.1. Long-term contractual agreement/commitment?
4.2.2.2. Co-location of resources?
4.2.2.3. Joint program/problem solving/learning/co-ordination?
4.2.3. Would you like to improve your relationships? Why and how?

4.3. Information sharing
4.3.1. How does the company ensure smooth flow of information across and between elements of the value chain?
4.3.2. What types of information do you share with other elements?
4.3.3. Does the company equipped with advanced Information and Communication Technology?

5. **Product Variety**
5.1. How do you consider/perceived product variety?
5.2. What are the major attributes that make one product different to another?
5.3. Which of the factors below that drives (become the source of) product variety:
5.3.1. Differences in raw materials used for different products?
5.3.2. Differences in design?
5.3.3. Differences in production process?
5.3.4. Different part/Accessories used?
5.4. How does variety affect the operation of international supply networks
5.4.1. Does production of different products require set-up activities?
5.4.2. Does the severity of set-up vary for different attributes?
5.4.3. What are other implications of product variety?
5.5. What are the company approaches to deal with increasing product variety?
5.5.1. Do they try to use more standard materials?
5.5.2. Do they apply 'postponement' concept to some extent?

6. **Challenges**
6.1. Does the company experience fluctuation in demand (both in terms of volume and mix)? How do they cope with this problem?
6.2. How good is the company in predicting demand? <u>Where applicable</u>:

APPENDIX 2 ROLLING FORECAST SYSTEM

The four case companies that are used as base for model development use a *rolling forecast system* in their production planning and control. In a rolling forecast system, every month the internal customer provides demand and forecast information for a certain period in the future. In the following month, the forecast with periods that have not passed may be updated and a new forecast is added as the last forecast. An example of the rolling forecast system is illustrated in figure A2.1.

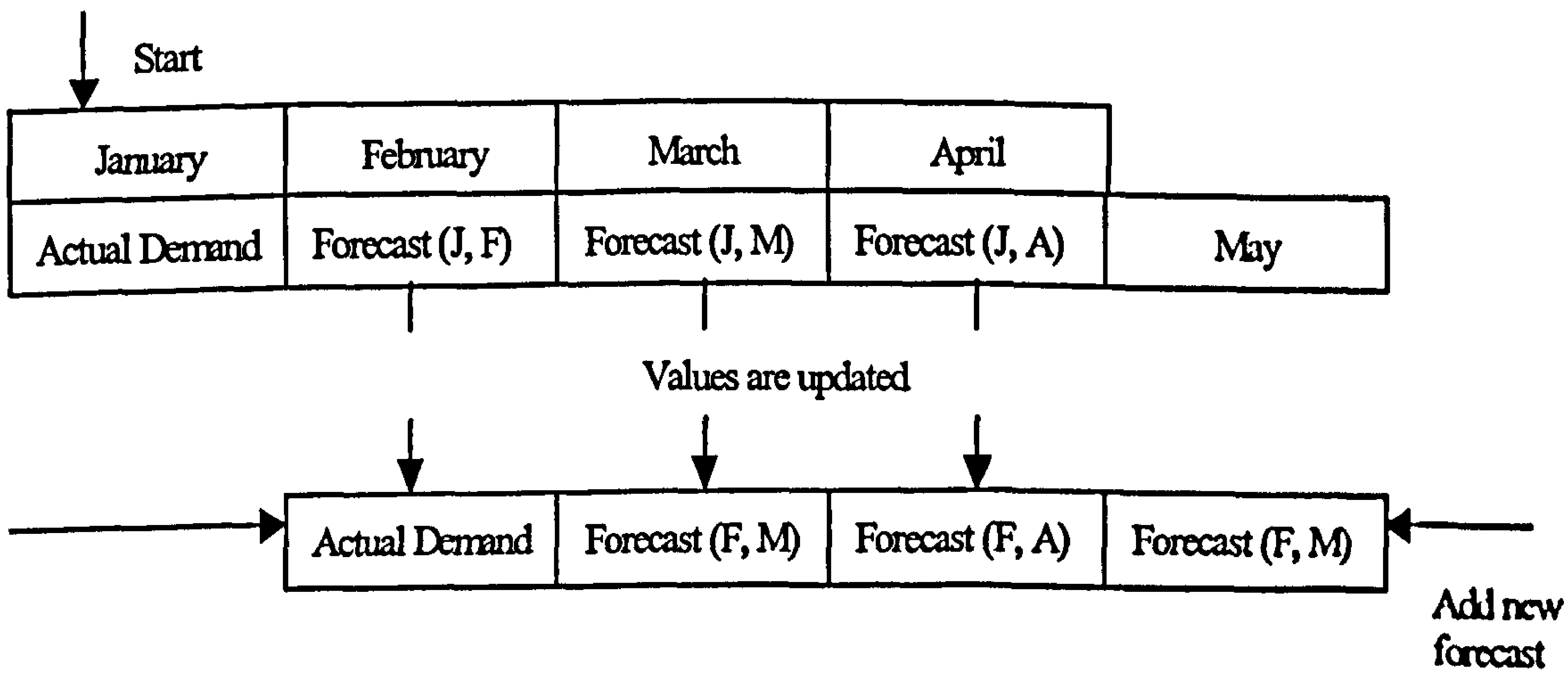


Figure A2.1 Illustration of Rolling Forecast System

In an ideal situation where the forecast given in one period is 'frozen' i.e. the values cannot be changed, the number provided in Forecast (J, F) will be the actual demand in February, Forecast (F, M) will equal to Forecast (J, M) and so on. However, in reality, forecast always contains error. As the actual period approaches the internal customer might have more knowledge and therefore the forecast is changed to reflect the current demand situation. As shown in figure 4.2, as the system roll to February, Forecast (J, M) might be updated and become Forecast (F, M) and Forecast (J, A) might be updated into Forecast (F, A). At the same time a new forecast, Forecast (F, M), is added.

Forecast information are required to determine volume and type of material to be ordered from supplier i.e. purchase order. The longer the expected lead-time to buy materials, the earlier they need to be bought based on forecast. Thus, the forecast needs to be made further ahead from the actual production (consumption) time.

APPENDIX 3 PILOT EXPERIMENT 1: SETTING THE RANGE OF SUPPLY LEAD-TIME

Pilot experiment 1 is conducted to investigate the impact of different levels of uncertainty on the performance of international supply chains and to choose a good set of values for each type of supply delivery time to be used in subsequent experiments. Before carrying out the experiments, several aspects of triangular distribution need to be explored.

Properties of Triangular Distribution

Several important properties of Triangular Distribution are as follow:

a = minimum, b = maximum, c = mode

$$\text{Mean} = \frac{a + b + c}{3} \qquad (1)$$

The level of uncertainty generated by the triangular distribution can be observed from the variance and standard deviation. When the distribution is symmetrical, b - a = 2 (c – a) and hence the mean equals the mode.

$$\text{Variance} = \frac{a^2 + b^2 + c^2 - ab - ac - bc}{18} \qquad (2)$$

$$\text{Standard Deviation} = \sqrt{\text{Variance}} \qquad (3)$$

In addition to variance and standard deviation, a valuable measure of the level of uncertainty is Coefficient of Variation (CV), which equals to:

$$\frac{\text{Standard Deviation}}{\text{Mean}}$$

While variance and standard deviation measure the 'absolute' variability, CV measures uncertainty relative to the average (mean) value. Based on the information from the case companies, the expected delivery time of global supplier (mode and mean) is greater (60 days) than local (20 days) suppliers. Two points can be derived:

- The same spread (maximum-minimum) or standard deviation will lead to smaller CV for global supplier.
- For the same value of CV, the spread or standard deviation for global will be greater than for local supplier.

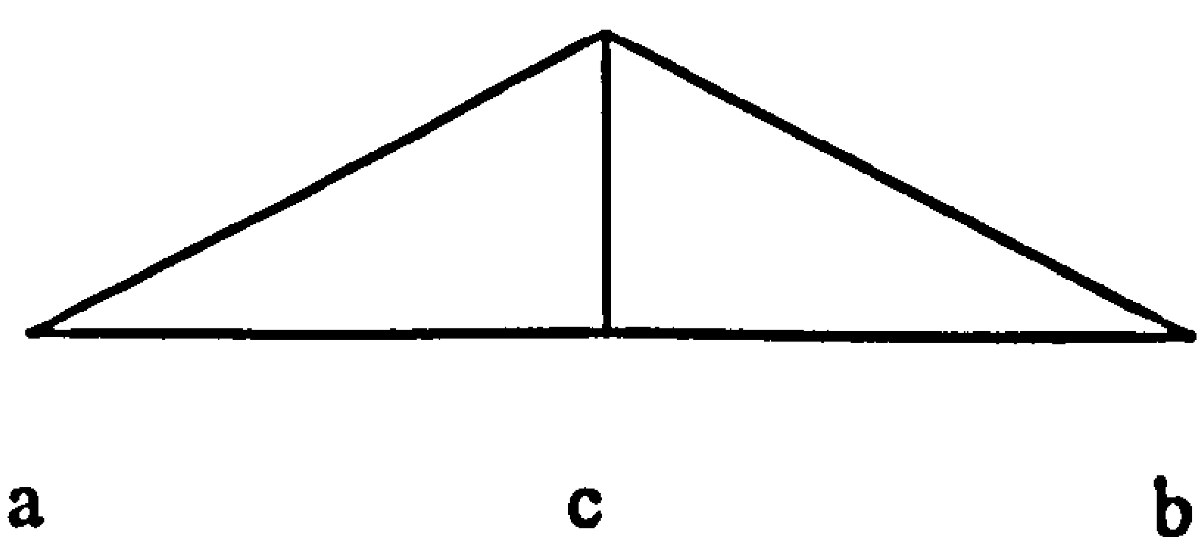
In order to ensure that the results between the two types of suppliers in this study are comparable, the CV between local and global supplier are set to be approximately equal. Thus, the standard deviation (the spread from expected delivery time) of global supplier is expected to be wider than for a local supplier. This is in alignment with reality, where buying from global supplier has more uncertainty in delivery associated with unexpected delay in sea shipment, export and import documentation, custom etc compare to local supplier.

Before setting up the values that will represent the distribution of supplier's lead-time, the relationships between range (maximum – minimum values), standard deviation and CV of the triangular distribution is explored. Table A3.1 presents several combinations of values for triangular distribution that leads to different standard deviations and CV. The shape of the triangular distribution is kept symmetrical. Thus, mean equals to mode and the minimum value for a is set to be 1.

Table A3.1 Exploring Different Level of Coefficient of Variation

Min (a)	Max (b)	Mode (c)	A^2	b^2	c^2	a x b	a x c	b x c	Variance	Std. Dev	CV
50	150	100	2500	22500	10000	7500	5000	15000	416.67	20.41	0.20
25	175	100	625	30625	10000	4375	2500	17500	937.50	30.62	0.31
1	199	100	1	39601	10000	199	100	19900	1633.50	40.42	0.40
150	250	200	22500	62500	40000	37500	30000	50000	416.67	20.41	0.10
100	300	200	10000	90000	40000	30000	20000	60000	1666.67	40.82	0.20
50	350	200	2500	122500	40000	17500	10000	70000	3750.00	61.24	0.31
1	399	200	1	159201	40000	399	200	79800	6600.17	81.24	0.41
500	1500	1000	250000	2250000	1000000	750000	500000	1500000	41666.67	204.12	0.20
250	1750	1000	62500	3062500	1000000	437500	250000	1750000	93750.00	306.19	0.31
100	1900	1000	10000	3610000	1000000	190000	100000	1900000	135000.00	367.42	0.37
50	1950	1000	2500	3802500	1000000	97500	50000	1950000	150416.67	387.84	0.39
25	1975	1000	625	3900625	1000000	49375	25000	1975000	158437.50	398.04	0.40
1	1999	1000	1	3996001	1000000	1999	1000	1999000	166333.50	407.84	0.41

It can be shown that when the range is symmetrical and the minimum value is set to be greater than zero, the maximum Coefficient of Variation of a triangular distribution is approximately 40%, irrespective of the values given for the mode (mean). This is related to the properties of Triangular Distribution and can be proven mathematically.



If the distribution is symmetrical, then:

$b - a = 2\,(c - a)$

$b = 2c - a$

Substituting b with $(2c - a)$:

$\text{Mean} = (a + b + c) / 3 = (a + 2c - a + c)/3 = c$

$\text{Variance} = (a^2 + b^2 + c^2 - ab - ac - bc)/18$

$\text{Variance} = (3a^2 + 3c^2 - 6ac)/18 = (a^2 + c^2 - 2ac)/6$

Then, using these values

$$CV = \frac{\sqrt{(a^2 + c^2 - 2ac)/6}}{c}$$

$$= \sqrt{\frac{(a^2 + c^2 - 2ac)}{6c^2}}$$

$$= \sqrt{\frac{a^2}{6c^2} + \frac{c^2}{6c^2} + \frac{2ac}{6c^2}}$$

When the value for a is very small (a >=1) while the value for c is very big, we can calculate that:

$$CV(\lim a \rightarrow 0, c \rightarrow \infty) = \sqrt{\frac{c^2}{6c^2}} = \sqrt{\frac{1}{6}} = 0.4082$$

Insights obtained from exploring the relationships among spread, standard deviation and CV of triangular distribution will be used as bases in designing the pilot experiments.

Several combinations of value and shape (symmetrical and asymmetrical) of triangular distribution representing different degrees of uncertainty (CV) will be tried in the pilot experiments. The expected time of supplier's delivery time obtained from the empirical results are used as a basis in setting up the minimum and maximum values of the triangular distribution. Several levels of CV are considered. In each level, the range (minimum and maximum) from expected delivery time (mode) of each type of supplier is determined (Table A3.2). The maximum CV for local supplier (average 20 days) is 38.78%, while in global supplier the maximum CV is 40.14%. In order to have more comparable results between local and global supplier, for symmetrical distribution the maximum CV to be investigated is set to be 38.78%.

Table A3.2 Symmetrical values of triangular distribution resulting in increasing level of CV for each type of supplier

Local						Global					
Min	max	mode	Variance	Std. Dev	CV	min	max	mode	Variance	Std. Dev	CV
15	25	20	4.17	2.041	0.10	45	75	60	37.50	6.124	0.10
10	30	20	16.67	4.082	0.20	30	90	60	150.00	12.247	0.20
5	35	20	37.50	6.124	0.31	15	105	60	337.50	18.371	0.31
1	39	20	60.17	7.757	0.39	3	117	60	541.50	23.270	0.39
						1	119	60	580.17	24.087	0.40

In order to investigate further the impact of higher uncertainty (CV) on the performance of a supply chain, several experiments with asymmetrical-shape triangular distribution are considered for each type of supplier. The values for asymmetrical triangular distribution are shown in table A3.3 In asymmetrical experiments for local supplier the minimum value (a) is assumed to be 5 days, while the minimum value for global supplier is assumed to be 15 days. Different levels of CV are obtained by changing the maximum value (b) for a triangular distribution.

Table A3.3 Asymmetrical values of triangular distribution resulting in high CV for each type of supplier

Min	Max	Mode	Mean	Variance	Std. Dev	CV	Min	Max	Mode	Mean	Variance	Std.Dev	CV
5	60	20	28.33	134.72	11.61	0.41	15	180	60	85	1212.5	34.82	0.41
5	75	20	33.33	226.39	15.05	0.45	15	225	60	100	2037.5	45.14	0.45
5	100	20	41.67	434.72	20.85	0.50	15	300	60	125	3912.5	62.55	0.50
5	150	20	58.33	1059.72	32.56	0.56	15	450	60	175	9537.5	97.66	0.56
5	250	20	91.67	3143.06	56.06	0.61	15	750	60	275	28287.5	168.19	0.61

Pilot experiments to determine range of supply delivery time

Design of pilot experiment 1

In this set of pilot experiments, main material supply lead-time is set as the main experimental factor while other factors are kept constant. Different types of supplier (local or global) and different values for triangular distribution as presented in table A3.2 and table A3.3 are tried to control the main material supply lead-time.

The experiments are first classified according to the type of supplier. Experiment P.L.1 – P.L.9 representing experiments for local supplier. Experiment P.L.1 – P.L.4 explores different levels of CV when the shape of the distribution is symmetrical while the rest five experiments explore asymmetrical shape of triangular distribution (P.L.5-P.L.9). Similarly, experiment P.G.1 – P.G.9 are conducted for global supplier, with the first five experiments look at symmetrical followed by asymmetrical triangular distribution. A complete design of pilot experiments is shown in table A3.4.

Table A3.4 Design of pilot experiments 1

Experiment number	Supply Type	Shape	Triangular Distribution			Variance	Standard Deviation	Coefficient of variation
			Minimum	Maximum	Mode			
Experiment P.L.1	Local	Symmetrical	15	25	20	4.2	2.04	0.10
Experiment P.L.2	Local	Symmetrical	10	30	20	16.7	4.08	0.20
Experiment P.L.3	Local	Symmetrical	5	35	20	37.5	6.12	0.31
Experiment P.L.4	Local	Symmetrical	1	39	20	60.2	7.76	0.39
Experiment P.L.5	Local	Asymmetrical	5	60	20	134.7	11.61	0.41
Experiment P.L.6	Local	Asymmetrical	5	75	20	226.4	15.05	0.45
Experiment P.L.7	Local	Asymmetrical	5	100	20	434.7	20.85	0.50
Experiment P.L.8	Local	Asymmetrical	5	150	20	1059.7	32.55	0.56
Experiment P.L.9	Local	Asymmetrical	5	250	20	3143.1	56.06	0.61
Experiment P.G.1	Global	Symmetrical	45	75	60	37.5	6.12	0.10
Experiment P.G.2	Global	Symmetrical	30	90	60	150.0	12.25	0.20
Experiment P.G.3	Global	Symmetrical	15	105	60	337.5	18.37	0.31
Experiment P.G.4	Global	Symmetrical	3	117	60	541.5	23.27	0.39
Experiment P.G.5	Global	Asymmetrical	15	180	60	1212.5	34.82	0.41
Experiment P.G.6	Global	Asymmetrical	15	225	60	2037.5	45.14	0.45
Experiment P.G.7	Global	Asymmetrical	15	300	60	3912.5	62.55	0.50
Experiment P.G.8	Global	Asymmetrical	15	450	60	9537.5	97.66	0.56
Experiment P.G.9	Global	Asymmetrical	15	750	60	28287.5	168.19	0.61

Results of pilot experiment 1

The shape of triangular distribution (symmetrical or asymmetrical) is expected to have a significant impact on the supply chain performances. Thus, a separate analysis will be conducted for each shape of the distribution. This will be followed by overall analysis on the impact of increasing uncertainty (CV) on the performance of the supply chain. Results obtained from experiments with symmetrical triangular distributions are summarised in table A3.5, while results from experiments with asymmetrical triangular distribution are summarised in table A3.6.

Results from Symmetrical Triangular Distribution

Main Material Tardiness

When the shape of the triangular distribution is symmetrical, there is equal possibility of main material being delivered earlier or later than expected time. The first performance measure that is directly affected by uncertainty in delivery time is average main material tardiness. The average material tardiness for local and global supplier is shown in figure A3.1. It is clear that increasing uncertainty in delivery time results in significant increases in main material tardiness in both type of supplier.

Average Delay in Production due to Main Material Shortages

Lateness in main material delivery subsequently affects the average time production is delayed due to main material shortages (Figure A3.2). As the CV increases, the average delays due to main material shortage increase significantly in both cases.

Table A3.5. Summary of results from experiment with symmetrical triangular distribution

Measures	Unit of Measurement	P.L.1	P.L.2	P.L.3	P.L.4	P.G.1	P.G.2	P.G.3	P.G.4
Coefficient of Variance		0.10	0.20	0.31	0.39	0.10	0.20	0.31	0.39
Average Flow Time of Overall Product	Day/Product	8.20	9.07	10.19	11.08	10.19	13.26	15.35	16.68
Average Time Process Delayed due to Main Material Shortages	Day/Product	1.33	2.97	4.59	5.70	4.59	7.83	9.63	10.68
Average Main Material Tardiness	Day/late delivery	1.66	3.32	4.97	6.30	4.97	9.93	14.90	18.87
Average Main Material Inventory	Unit of Main Material	1192	1847	2510	2963	2510	3882	4850	5471
Average Unique Material Inventory	Unit of Unique Material	846	846	846	846	846	845	846	845
Average Packaging Material Inventory	Unit of Packaging Material	846	846	846	846	846	845	846	845
Average System Inventory	Unit of Inventory	2883	3538	4201	4654	4201	5572	6541	7162

Table A3.6. Summary of results from experiment with asymmetrical triangular distribution

Measures	Unit of Measurement	P.L.5	P.L.6	P.L.7	P.L.8	P.L.9	P.G.5	P.G.6	P.G.7	P.G.8	P.G.9
Coefficient of Variance		0.41	0.45	0.50	0.56	0.61	0.41	0.45	0.50	0.56	0.61
Average Flow Time of Overall Product	Day/Product	19.87	26.65	42.23	80.65	154.56	54.23	89.80	139.24	262.91	525.40
Average Time Process Delayed due to Main Material Shortages	Day/Product	10.80	13.84	19.51	33.49	57.72	22.91	34.47	49.30	90.72	186.36
Average Main Material Tardiness	Day/late delivery	13.13	18.32	27.02	43.72	74.36	40.72	55.36	77.24	126.34	233.06
Average Main Material Inventory	Unit of Main Material	1085	601	283	170	117	885	538	465	224	42
Average Unique Material Inventory	Unit of Unique Material	845	845	845	846	846	846	846	845	846	846
Average Packaging Material Inventory	Unit of Packaging Material	845	845	845	846	846	846	846	845	846	846
Average System Inventory	Unit of Inventory	2776	2292	1974	1861	1809	2576	2229	2156	1916	1733

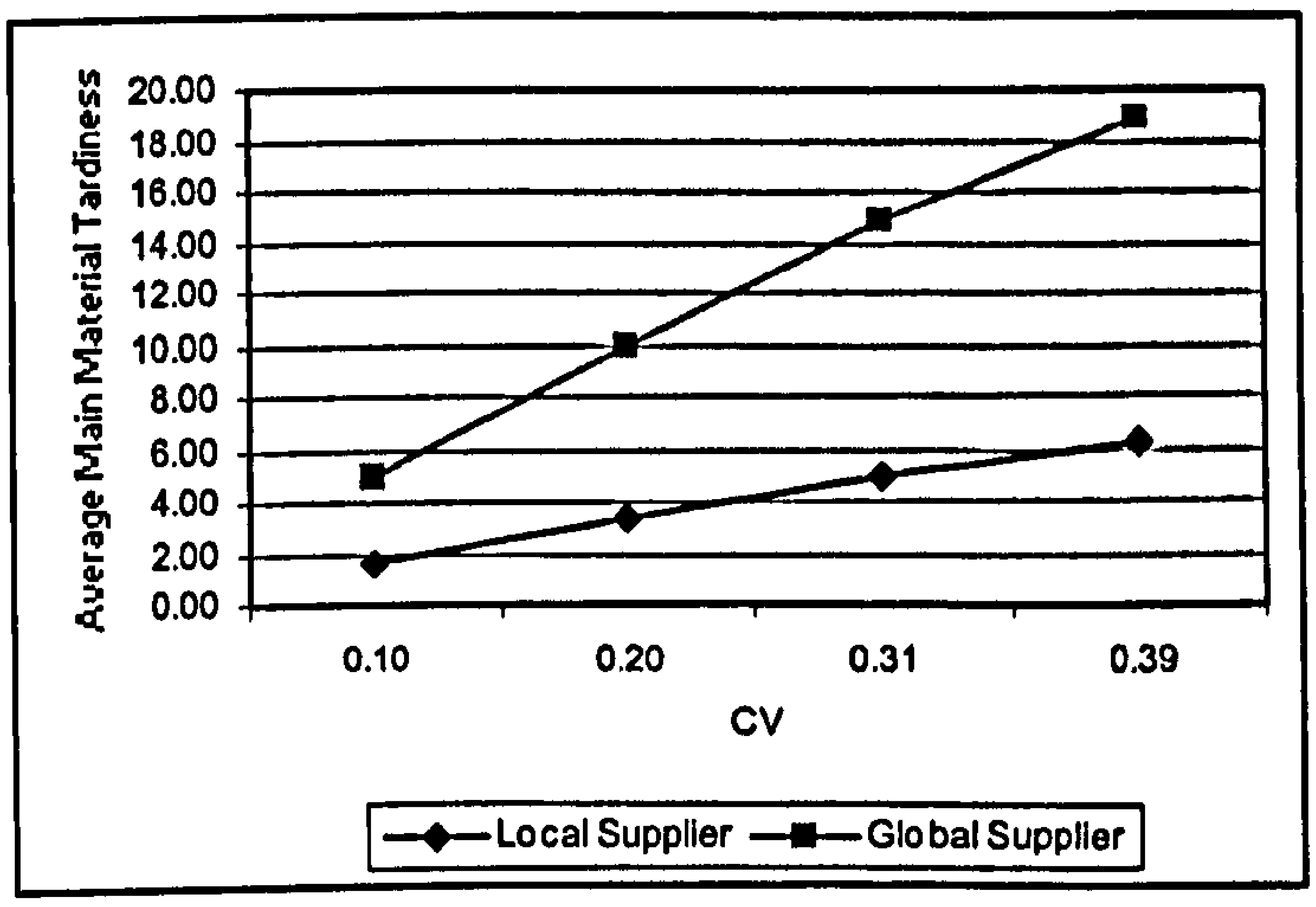


Figure A3.1 Impact of Increasing CV in Symmetrical Triangular Distribution on Average Main Material Tardiness

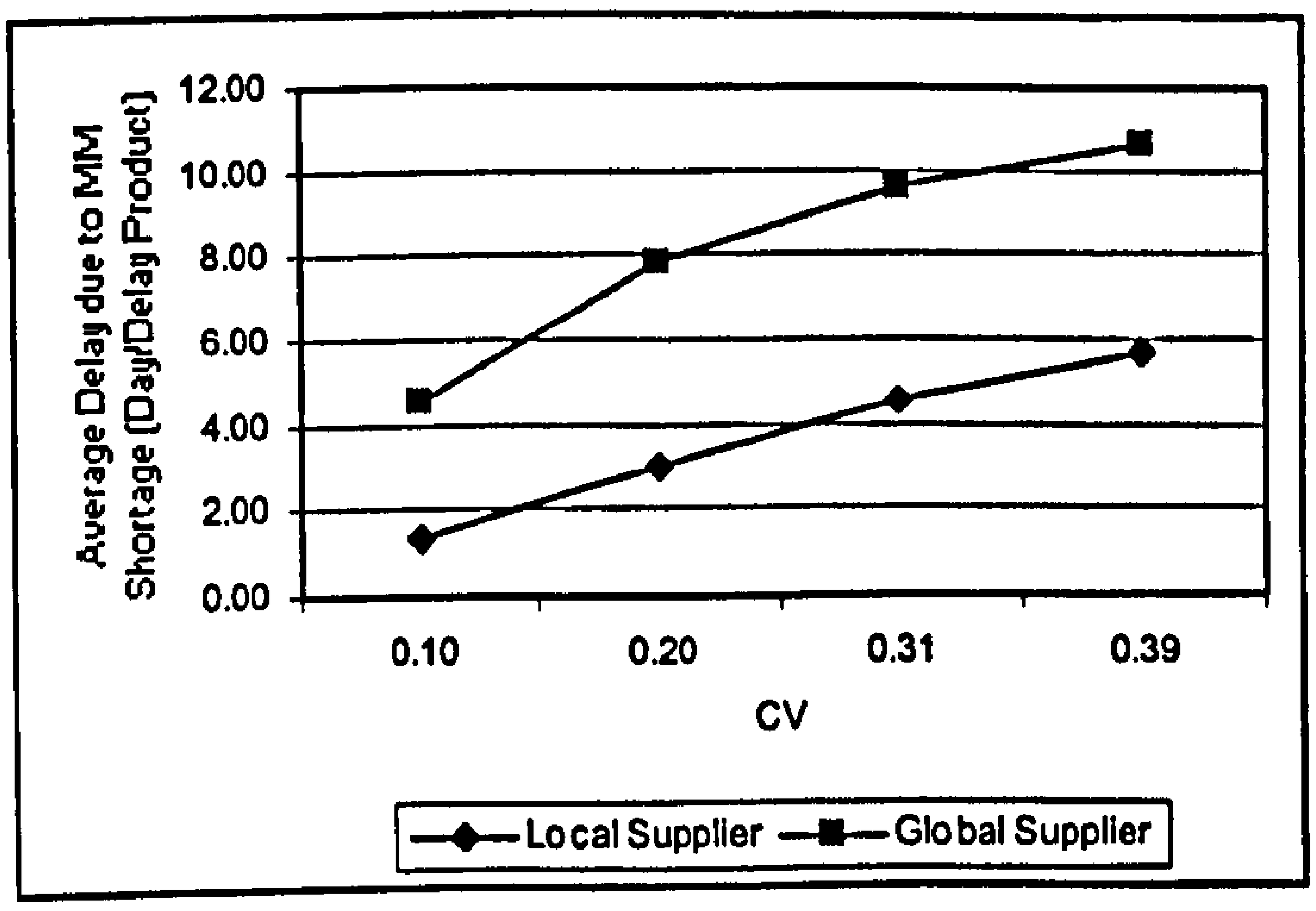


Figure A3.2. Impact of Increasing CV in Symmetrical Triangular Distribution on Average Delay due to Main Material Shortage

Average Flow Time

In alignment with increasing length of delay in production due to main material shortages, the average flow time in both types of suppliers increase with increasing CV (figure A3.3).

Average Main Material Inventory

In this set of pilot experiments, delivery time of main material is set to be variable. This has a significant impact on the amount of inventory held in stock. While the previous measures are mainly affected by lateness in main material delivery, measure of main material inventory is more affected by deliveries made earlier than expected. When material is late, the main impact is delay in production. However, when material arrives earlier than expected time, the system will have to hold the material longer than expected. The increase in holding time subsequently increases the average amount of inventory held in stock. As shown in figure A3.4, increasing CV means greater possibilities that material delivered far earlier than expected time. This eventually led to increasing level of average of main material held in stock. The impact of increasing supply delivery uncertainty on the average inventory is more significant for global suppliers.

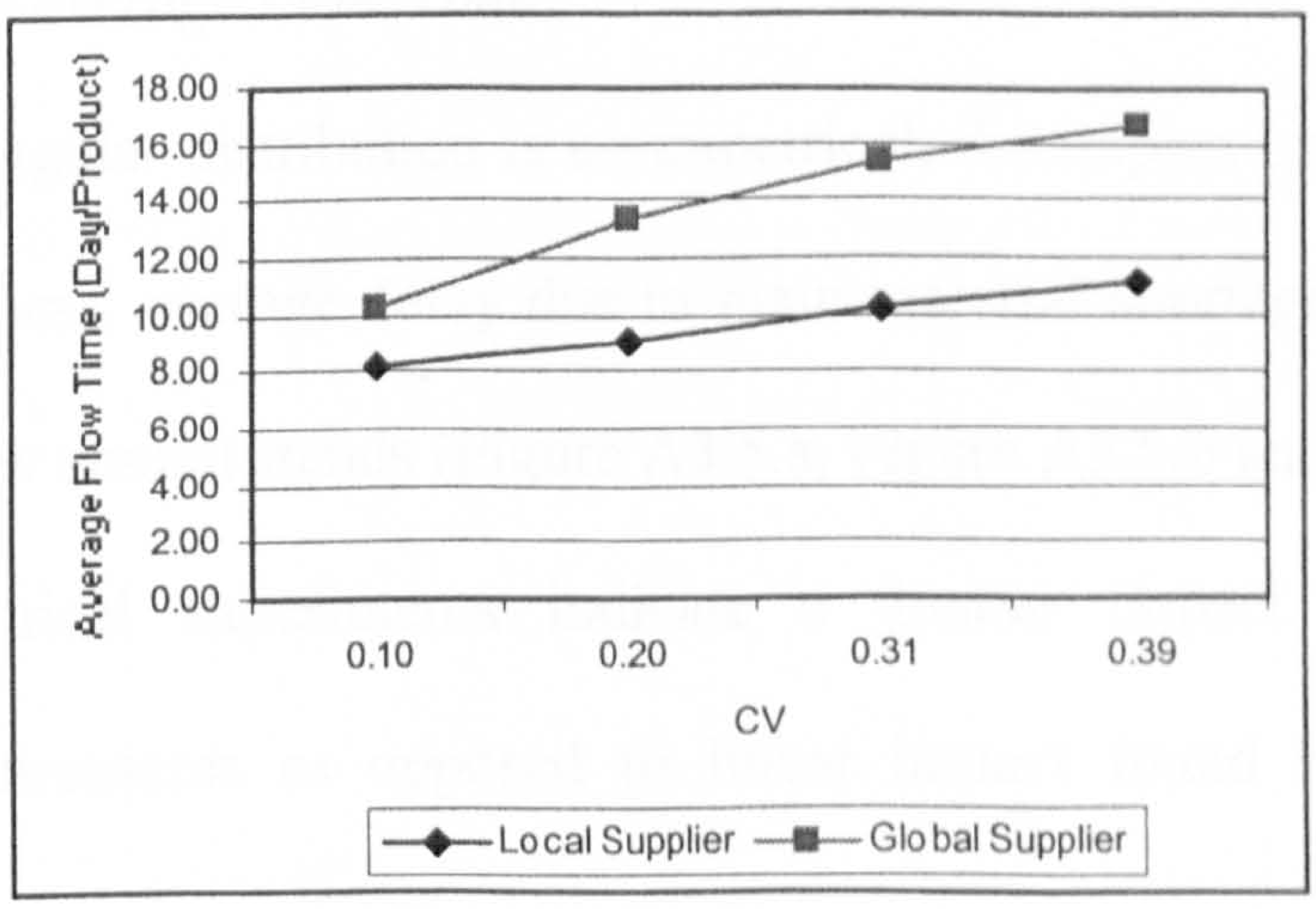


Figure A3.3. Impact of Increasing C.V in Symmetrical Triangular Distribution on Average Flow Time

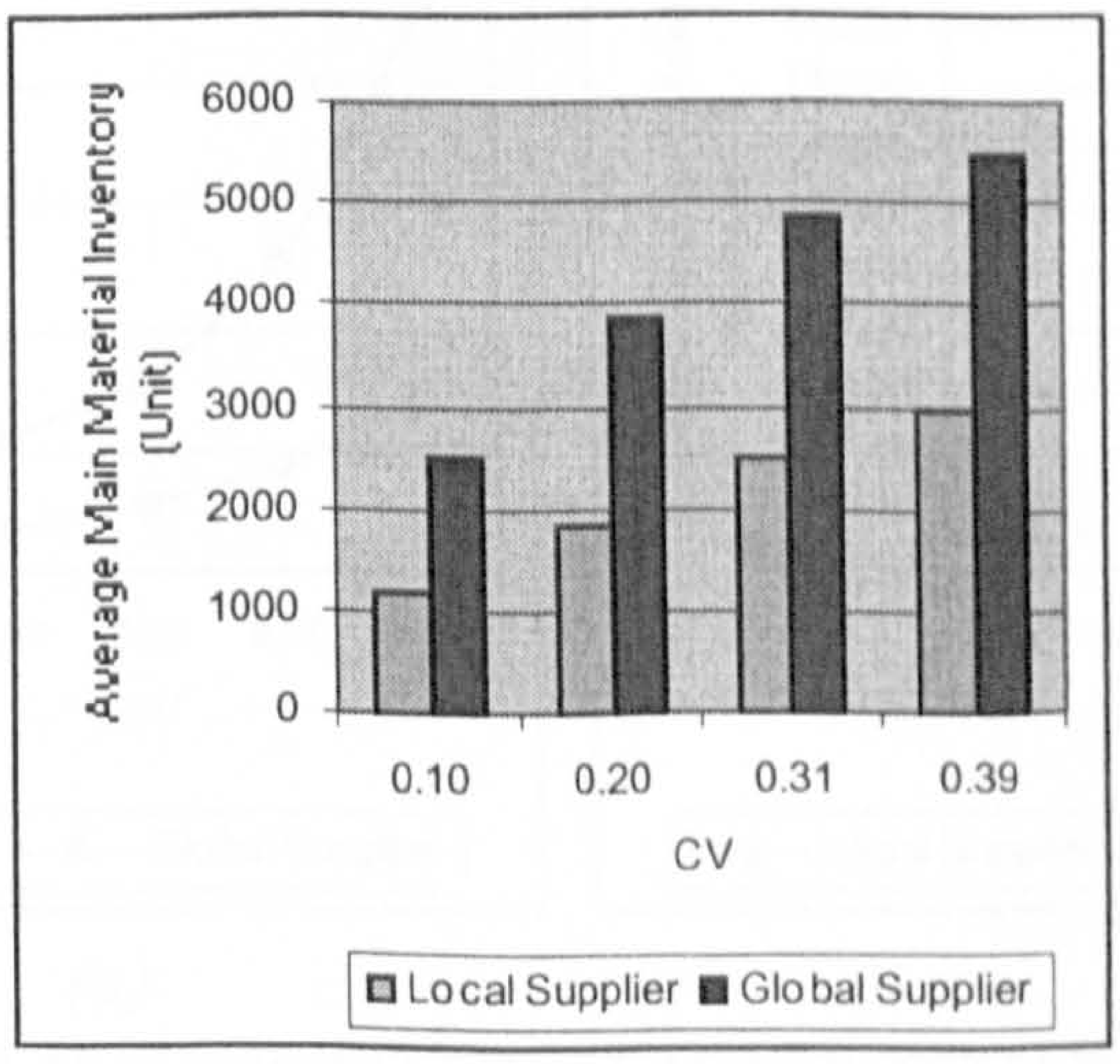


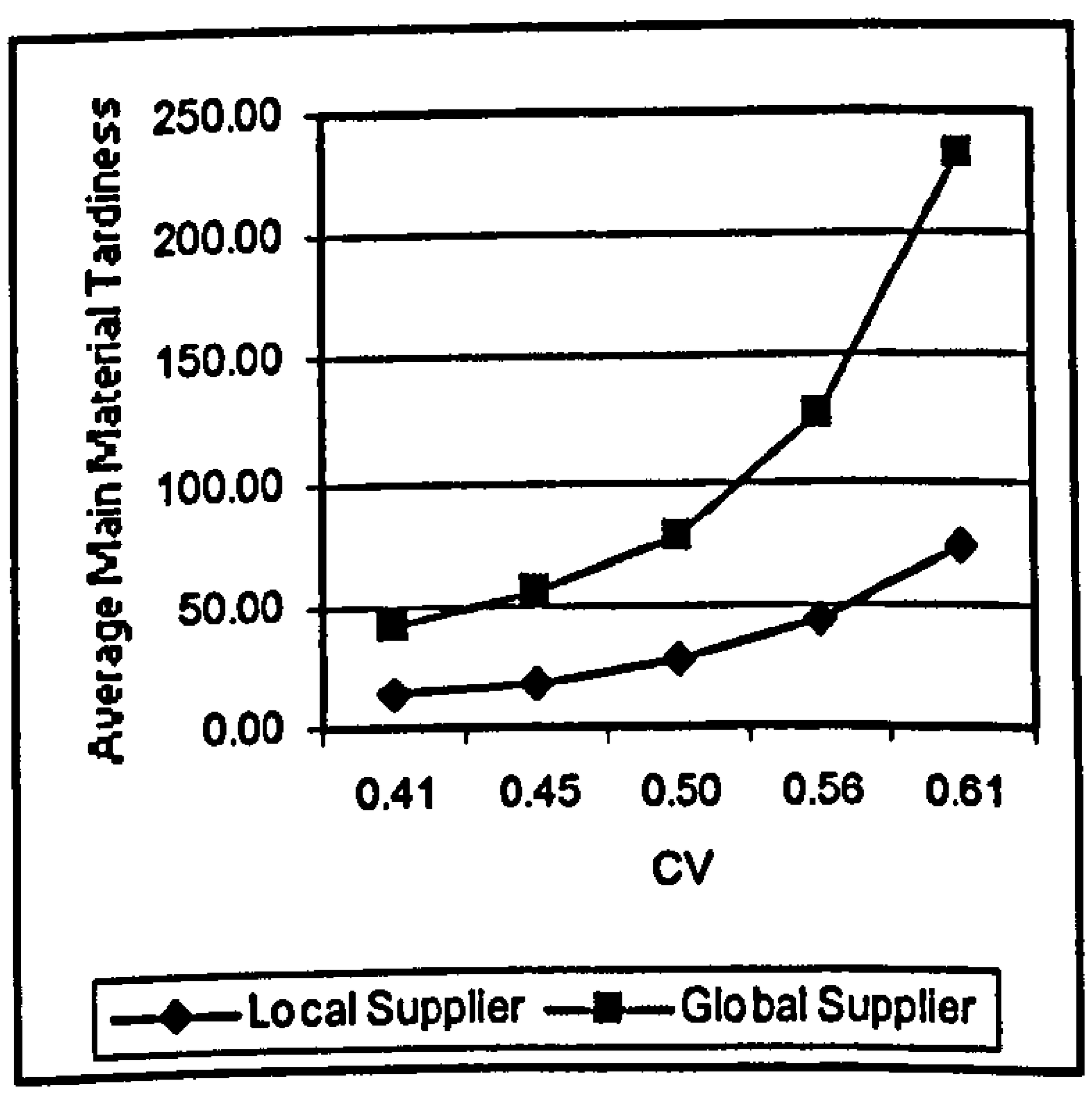
Figure A3.4. Impact of increasing CV in Symmetrical triangular distribution on Average Main Material Inventory

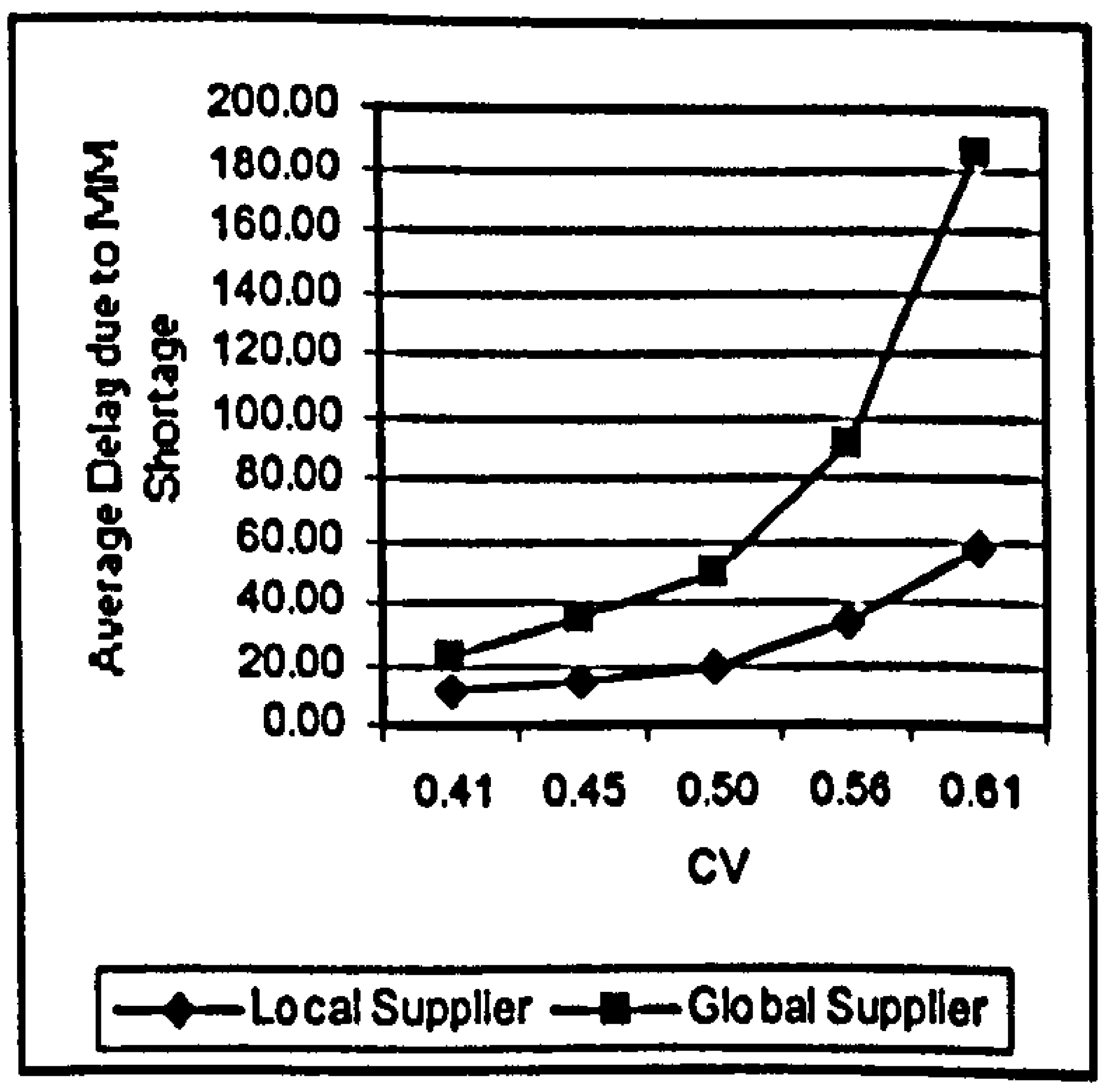
Results from Asymmetrical Triangular Distribution

Results from experiments with asymmetrical triangular distribution are presented in Table A3.6. In these experiments, increasing the level of uncertainty (CV) is achieved by increasing the maximum value for triangular distribution (b) allowing a wider spread of maximum – mode. This means there is a higher proportion of product being delivered late than early compared to equal proportions of late and early delivery in the symmetrical distribution.

Average Main Material Tardiness, Average Delay due to Main Material Shortages and Average Flow Time

When the triangular distribution is asymmetrical, the impact on average main material tardiness, average delay due to main material shortages and average flow time show similar trends (Figure A3.5.a, Figure A3.5.b and Figure A3.6). The asymmetrical experiments indicate a greater impact on the three performance measures as opposed to linear impact found in symmetrical experiments.





(a) *(b)*

Figure A3.5 Impact of increasing CV of asymmetrical triangular distribution on main material tardiness (a) and average delay due to main material shortage (b)

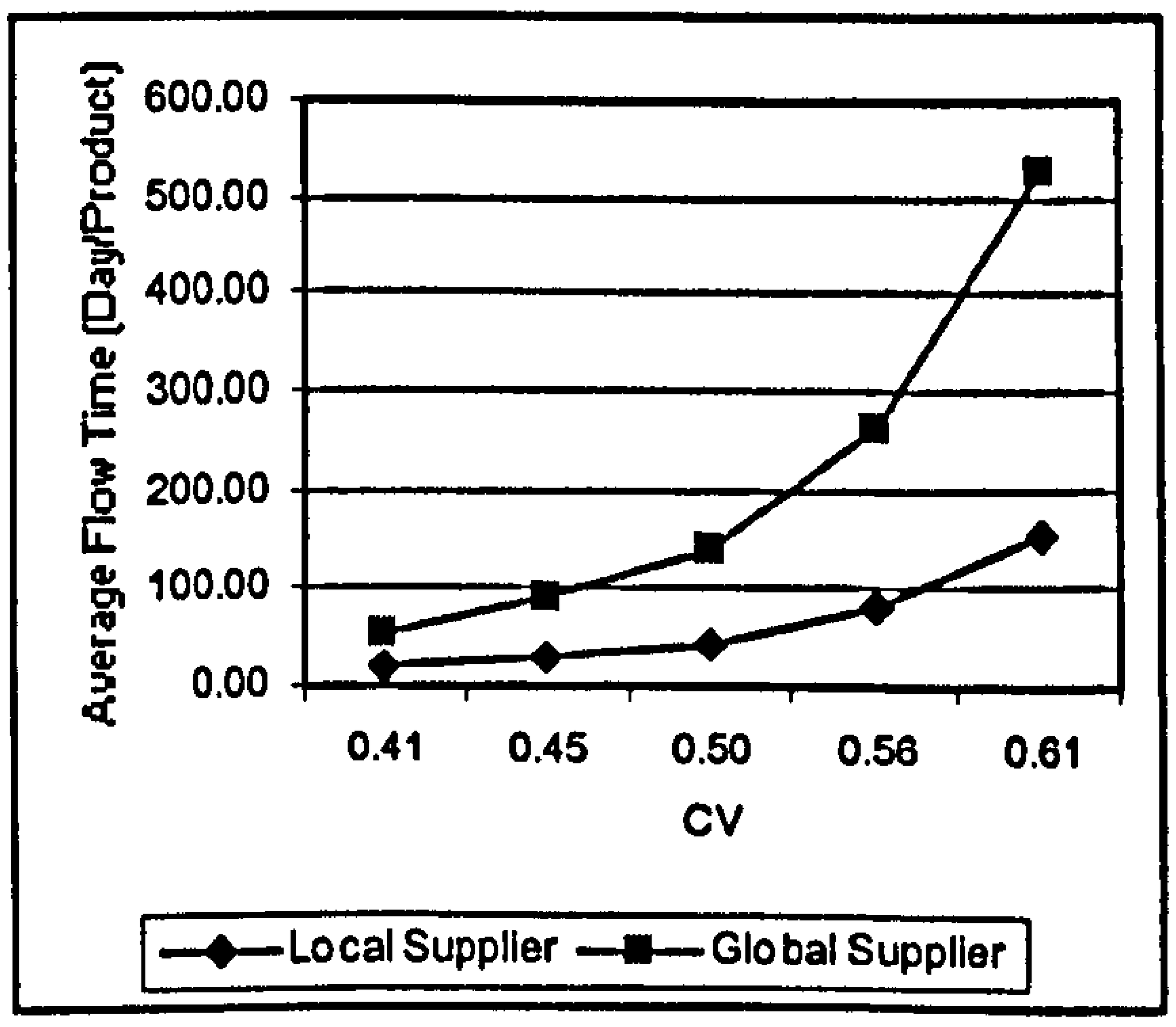


Figure A3.6 Impact of increasing CV of asymmetrical triangular distribution on average flow time

When the shape of the triangular distribution is asymmetrical, increasing CV leads to different impact on average main material inventory compared to the impact found in symmetrical distribution. As discussed previously, average main material inventory is affected by the amount of material arriving earlier than expected.

In symmetrical experiment, increasing CV is obtained by moving both minimum and maximum value further from the mode. Thus, increasing CV lead to higher inventory. However, in asymmetrical experiment, only the maximum value is moved further from the mode. This means the proportion of material arriving earlier than expected time decreases, which is expected to lead to decreasing level of average main material inventory. This is shown in figure A3.7 where increasing CV led to decreasing level of average main material inventory.

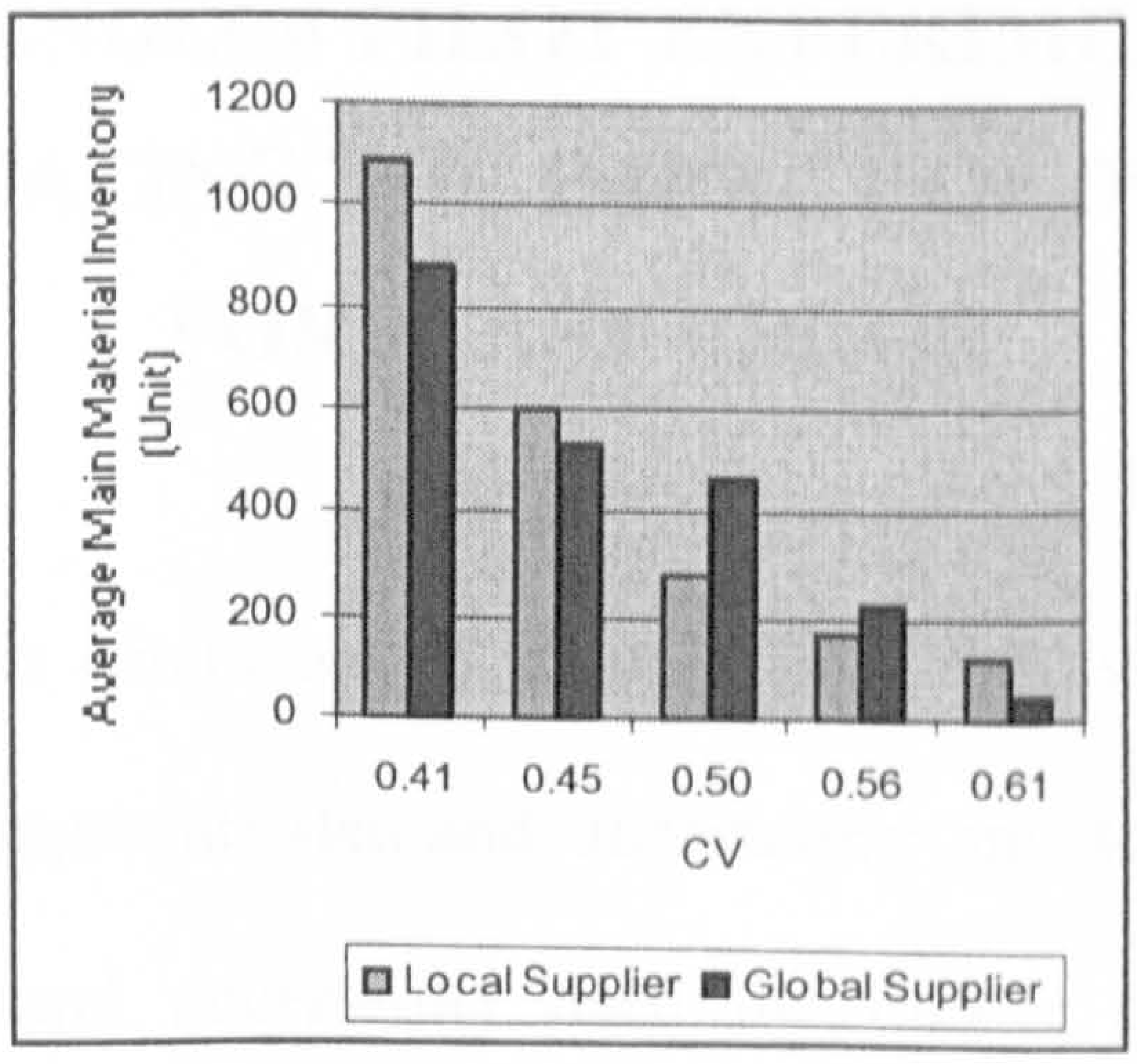


Figure A3.7 Impact of increasing CV in asymmetrical triangular distribution on average main material inventory

APPENDIX 4 PILOT EXPERIMENT 2: INVESTIGATING THE IMPACT OF DIFFERENT FORECAST ERROR

Pilot experiment 2 is conducted to explore how the system performs under different levels of aggregate-demand uncertainty and to justify the level of aggregate-level demand uncertainty used for further experimentation. The setting and design of pilot experiment 2 are summarised in table A4.1 and A4.2, respectively.

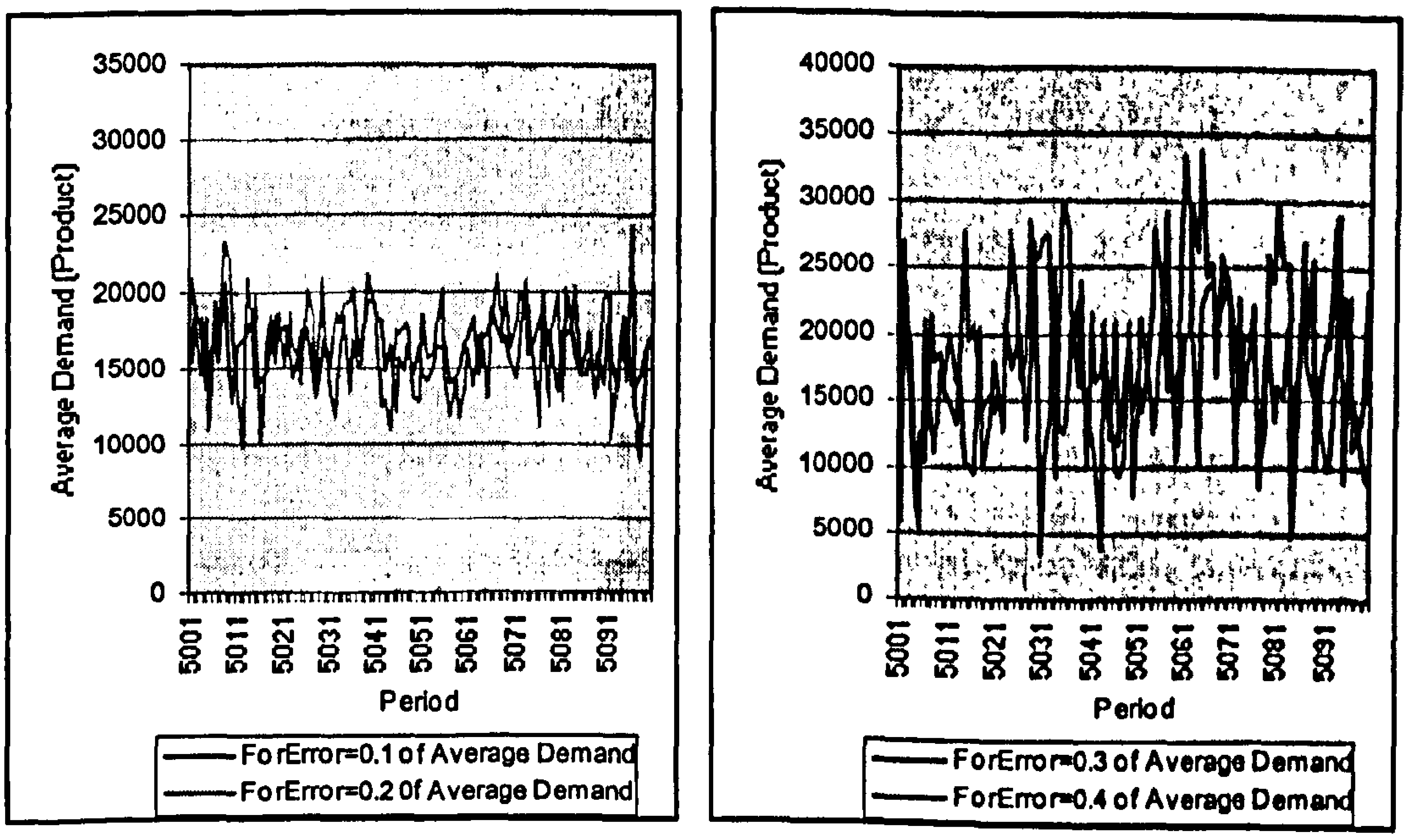
Table A4.1. Setting of pilot experiments 2

Factor	Level
Number of main material	1
Number of unique material	1
Number of packaging material	1
Supplier of main material	Local
Supplier of unique material	Local
Supplier of packaging material	Local
Product mix	Constant
Volume	Variable

Table A4.2 Design of pilot experiment 2

Experiment	Treatment
Experiment Pilot_ForError1	ForError = 0.1 x 16875 = 1687
Experiment Pilot_ForError2	ForError = 0.2 x 16875 = 3375
Experiment Pilot_ForError3	ForError = 0.3 x 16875 = 5062
Experiment Pilot_ForError4	ForError = 0.4 x 16875 = 6750

Figure A4.1 (a) and (b) show aggregate-level demand with four different forecast error factors. Clearly higher forecast errors (figure A4.1.b) lead to greater upswings and downswings of aggregate demand from the long-term average value (16,875 units).



(a) (b)

Figure A4.1. Aggregate –level demand with different forecast error

Results of the pilot experiment 2 on several supply chain performance measures are summarised in table A4.3. Despite differences in forecast error, the average aggregate-demand over the long-term in the each experiment is approaching 16,875. To verify the results, error of forecasts are determined by:

F(t, j) = forecast made in period t for period j

Error forecast 1 = actual demand (t) – forecast (t-1, 1)

Error forecast 2 = actual demand (t) – forecast (t-2, 2)

Results for both errors are averaged and standard deviations are determined.

In alignment with the assumption that errors is expected to be higher as the forecasts are made further from the actual demand, in all four experiments standard deviation of error forecast 2 (forecast made 2 month in advance) is higher than standard deviation or error forecast 1 (forecast made 1 month in advance).

Increasing the level of forecast error has a clear impact on the average of total inventory held in stock. The level of inventory for each type of material increases with increasing forecast error. The uncertainty in aggregate-level demand leads to a mismatch between materials ordered based on forecast and the actual requirement for production. This means that there are possibilities that production is delayed as there are shortages in material that subsequently lead to longer average flow time. As the level of uncertainty in demand increases with the increase in forecast error, the impacts on the average flow time slowly increases.

Table A4.3. Results of pilot experiments investigating the impact of different forecast error

Measures	Unit of measurement	Forecast Error 0.1	Forecast Error 0.2	Forecast Error 0.3	Forecast Error 0.4
Average aggregate-level demand	Unit	16860	16846	16825	16795
Standard Deviation Error Forecast 1		1673.09	3348.32	5031.53	6739.86
Standard Deviation Error Forecast 2		1814.90	3626.32	5425.34	7281.20
Average Flow Time	Day/Product	8.72	10.47	12.91	16.21
Average Time Process Delayed Due to Main Material Shortages	Day/Product	19.00	19.00	19.00	19.01
Average Time Process Delayed Due to Unique Material Shortages	Day/Product	0	0	0	0
Average Time Process Delayed Due to Packaging Material Shortages	Day/Product	0	0	0	0
Average Main Material Inventory	Unit of Main Material	1910	2941	3981	5176
Average Unique Material Inventory	Unit of Unique Material	1910	2941	3981	5176
Average Packaging Material Inventory	Unit of Packaging Material	1910	2941	3981	5176
Average System Inventory	Unit of Inventory	5731	8824	11942	15529

Results from pilot experiment 2 clearly indicate that increasing the level of forecast error i.e. increasing aggregate demand uncertainty results to worse supply chain performance. When the level of forecast error is set to 30% and 40% the upswing and downswing in demand is very high. In these situations, the system shows extreme results e.g. high inventory level and very long lead-time. These extreme results may obscure the impact of other factors. A 20% forecast error, on the other hand, results in reasonably good upswing and downswing with fewer occurrences of extreme values. Thus, the forecast error is set at 20% of the average aggregate level demand, as it provides a sufficiently good representation of volume uncertainty.

APPENDIX 5 VERIFICATION OF SIMULATION PROGRAM

In order to verify if the simulation program is correct, it is ran under the following settings:

- The most deterministic or normal situation
- Increasing product variety
- Uncertain aggregate-level demand (uncertain volume)
- Uncertain product-level demand (uncertain mix)

Results obtained from the above situations are described here.

- **Normal Conditions**

In the most deterministic situation, the system only produces one product, the volume of aggregate demand is constant, and the suppliers are local and deliver just in time. In this situation, the behaviour of the simulation can be easily predicted and the results can be calculated manually.

The model starts with no inventories in the system. Therefore, in several initial periods the demand generated is delayed, as there are no stocks of materials. This explains the results shown in table A5.1, where over 5,000 warming-up periods, 33,750 products are delayed. However, as the simulation progresses it will trigger replenishment of material stock. When the system reaches a steady state condition, stock will arrive at the end of month ready for production the following month. At the beginning of the following month, an aggregate demand of 16,875 units is generated and depletes the level of inventory to zero. Results from the measurement period in table A5.1 confirms this scenario by showing that in a steady state condition a total of 84,375,000 units of product (111) is generated and produced over 5,000 periods without any delay. Table A5.1 shows that in a normal situation, when a supplier delivers 'just in time' (every 20 days) without uncertainty in delivery time and the simulation has reached the steady state, there are no delays in the processes due to material shortages. This is confirmed by the results that show measures of delay due to material shortages are zero.

Table A5.1 General results in normal condition

Metrics	Total demand	Total delayed demand	Total non-delayed demand	Average time process delayed due to Main Material (MM) shortages	Average time process delayed due to Unique Material (MM) shortages	Average time process delayed due to Packaging Material (PM) shortages
(Unit)	(Product)	(Product)	(Product)	(Day/unit product)	(Day/unit product)	(Day/unit product)
Warm-up Period	84,375,000	33,750,000	84,341,250	29	0	0
Measurement Period	84,375,000	0	84,375,000	0	0	0

Table A5.2 presents the average of each type of material inventory held in stock over the simulated period. As the system only produces one type of product, there are only three different materials held in stock including main material type 1, unique material type 1 and packaging material type 1.

Table A5.2 Average materials inventory

Metrics	Average Main Material Type 1	Average Unique Material Type 1	Average Packaging Material Type 1
(Unit)	(Unit of MM)	(Unit of UM)	(Unit of PM)
Warm-up Period	845.33	845.33	845.33
Measurement Period	845.51	845.51	845.51

The average of each type of material inventory is calculated continuously throughout the simulation as a cumulative average using equation 5.2. In normal conditions as mentioned previously, 16,875 units of each type of material will be added to their respective stocks every 20 days. All the stocks will be used for production starting in day 1. For the programming purpose, 1 minute or 0.002083 day additional time is added for scheduling and allocating product-level demand after they are generated, in order to ensure that the batches are sequenced in the correct order. Therefore each stock will have a level of 16,875 units only for a period of 1.002083 day.

As shown in figure A5.1 the average of each type of material inventory can be calculated by accumulating area under the curve divided by the simulated time duration:

Average material inventory

$$= \frac{10{,}000 \times (16{,}875\text{unit of material} \times 1.002083 \text{ day})}{10{,}000 \text{ period} \times 20 \text{ days}}$$

$$= 169{,}101{,}506/200{,}000$$

$$= 845.507 \approx 846 \text{ unit of material/day}$$

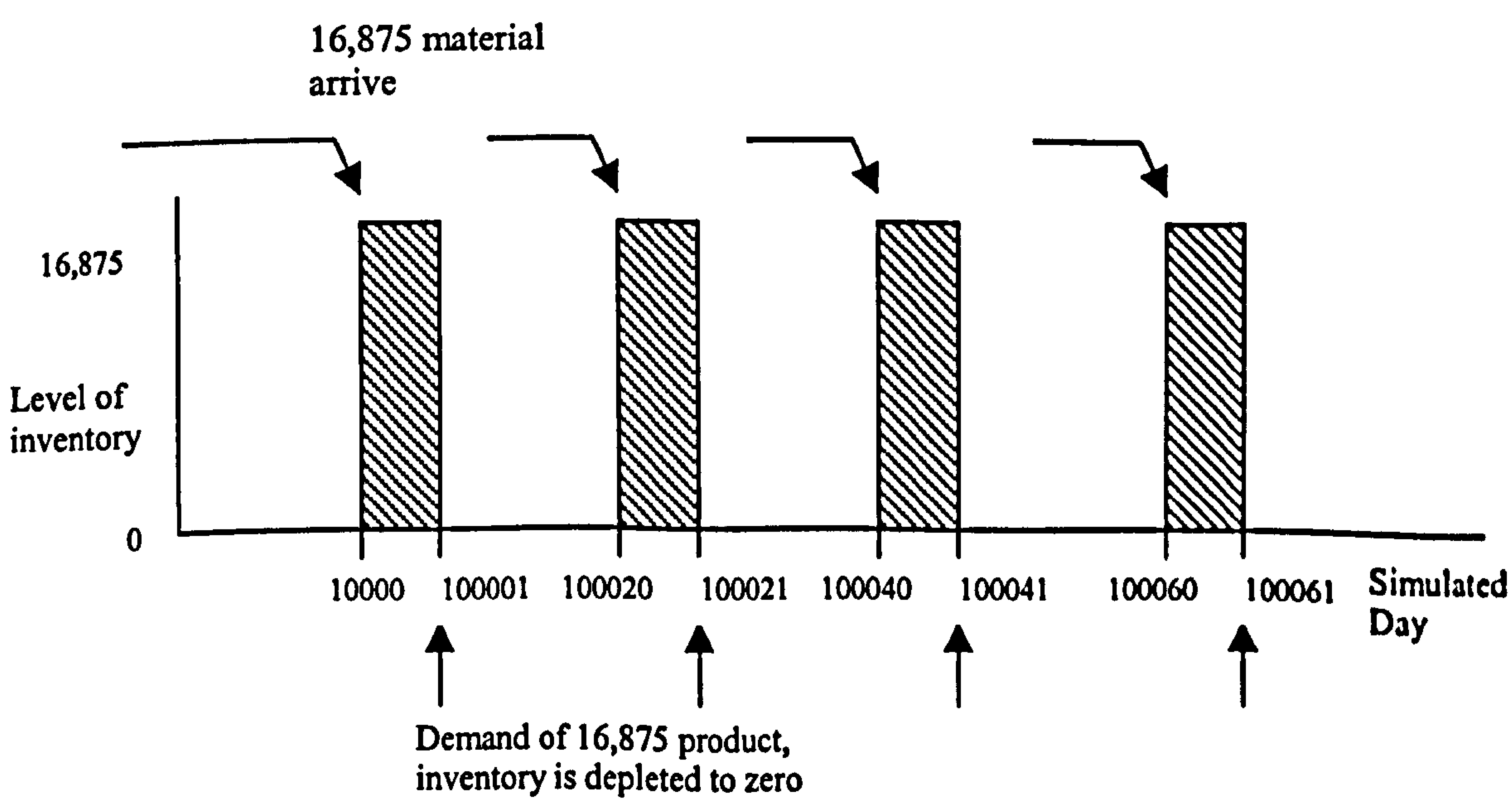


Figure A5.1 Calculation of average material inventory

Results presented in table A5.2 confirmed this calculation, indicating that the simulation is working as expected. In a normal situation, each type of material is held in stock at the level of 846 units/day leading to an overall material inventory of approximately 2,538.

Finally, table A5.3 presents measures of set-up, processing time and flow time in a normal situation. As the system only produces one type of product, no set-up times are incurred. Furthermore, there are no delays in getting the material for production. As shown in table A5.3, flow time per product in the base case equal to 7.78 days. This result is confirmed with a manual calculation using a spreadsheet.

Table A5.3 Processing time and flow time for base case

Metrics	Average Set-up Time for Process 1	Average Time in Process 1	Average Set-up Time for Process 2	Average Time in Process 2	Average Set-up for Process 3	Average Time in Process 3	Average Flow Time All Product
(Unit)	(Day/ Product)	(Day/ Product)	(Day/ Product)	(Day/ Product)	(Day/ Product)	(Day/ Product)	(Day/ Product)
Warm up period	0	0.1215	0	0.0972	0	0.0243	7.81
Measurement Period	0	0.1215	0	0.0972	0	0.0243	7.78

5.1.1 Verifying the mechanism generating product variety

In this study, the level of product variety is determined by the use of different materials. There are three different materials that can be the source of variety including main materials, unique materials and packaging materials. In order to investigate the impact of increasing product variety on the performance of the supply chain, several pilot experiments were conducted by increasing the number of main material options while there is only one option for both unique and packaging material.

Table A5.4 shows the proportion of each type of material obtained from the pilot experiment results, when the number of main material options is increased by one, from one option up to five options. As the number of options of main material increases, a greater number of product variants is produced. As shown in table A5.4, product-level demands for each product are fractions of the aggregate-level demand, which confirm that the mechanism to generate product-level demand is working as expected.

Table A5.4 Proportion (%) of each type of material and product-level demand when number of main material options is increased

No of main material	Proportion of main material type	No of unique material	Proportion of unique material (1)	No of packaging material	Proportion of packaging material (1)	Product Type (PM; MM; UM)	Product-level demand
1	1=1	1	1	1	1	111	16875
2	1=0.5	1	1	1	1	111	8437
	2=0.5	1	1	1	1	121	8438
3	1=0.33	1	1	1	1	111	5625
	2=0.33	1	1	1	1	121	5625
	3=0.33	1	1	1	1	131	5625
4	1=0.25	1	1	1	1	111	4218
	2=0.25	1	1	1	1	121	4218
	3=0.25	1	1	1	1	131	4218
	4=0.25	1	1	1	1	141	4221
5	1=0.2	1	1	1	1	111	3375
	2=0.2	1	1	1	1	121	3375
	3=0.2	1	1	1	1	131	3375
	4=0.2	1	1	1	1	141	3375
	5=0.2	1	1	1	1	151	3375

The number of different main material stocks that need to be managed increases with increasing number of main material options. The average inventory of individual main material stocks reduces in proportion with product-level demands as the number of main material options increases (table A5.5). The average inventory for unique and packaging material remains constant. Overall, the average of total inventory remains constant, as the aggregate-level demand is kept constant throughout the experiments.

Table A5.5 Average Inventory when number of main material options is increased

No of Main Material Option (MM)	Average Main Material					Average Unique Material	Average Packaging Material	Average of total inventory
	1	2	3	4	5			
1	846	0	0	0	0	846	846	2537
2	423	423	0	0	0	846	846	2537
3	282	282	282	0	0	846	846	2537
4	211	211	211	211	0	846	846	2537
5	169	169	169	169	169	846	846	2537

The average processing times and set-up times are shown in table A5.6. In general, the average processing times in each stage of the process change slightly as different product-level demands result in slightly different batch sizes. A more significant change is apparent in set-up time. Processing different types of main material sequentially in process 1 requires certain period for set-up. This is confirmed by the increase in the average set-up time of process 1 from zero in the base case to 0.75 day. As there is only 1 type of unique and packaging material to be processed in process 2 and 3, no set-ups occur in these processes.

Table A5.6 Average processing and set-up time when number of main material options is increased

Number of main material	Average Set-up time in process 1 (day)	Average time of process 1 (day)	Average Set-up time in process 2 (day)	Average time of process 2 (day)	Average Set-up time in process 3 (day)	Average time of process 3 (day)	Average flow time
1	0	0.1215	0	0.0972	0	0.0243	7.78
2	0.75	0.1225	0	0.0980	0	0.0245	8.91
3	0.75	0.1235	0	0.0988	0	0.0247	9.28
4	0.75	0.1225	0	0.0980	0	0.0245	9.66
5	0.75	0.1215	0	0.0972	0	0.0243	10.03

The occurrence of set-up time eventually contributed to longer average flow time. Figure A5.2 presents the average flow time when the number of main materials is increased. It is clear that increasing the number of main materials leads to a substantial increase in the average flow time. The most drastic increase in the average flow time is found when the number of main materials is increased from one to two options. Following the changes from one option to two options, the increase in the average flow time appears to be linear with the increase in the number of main material options.

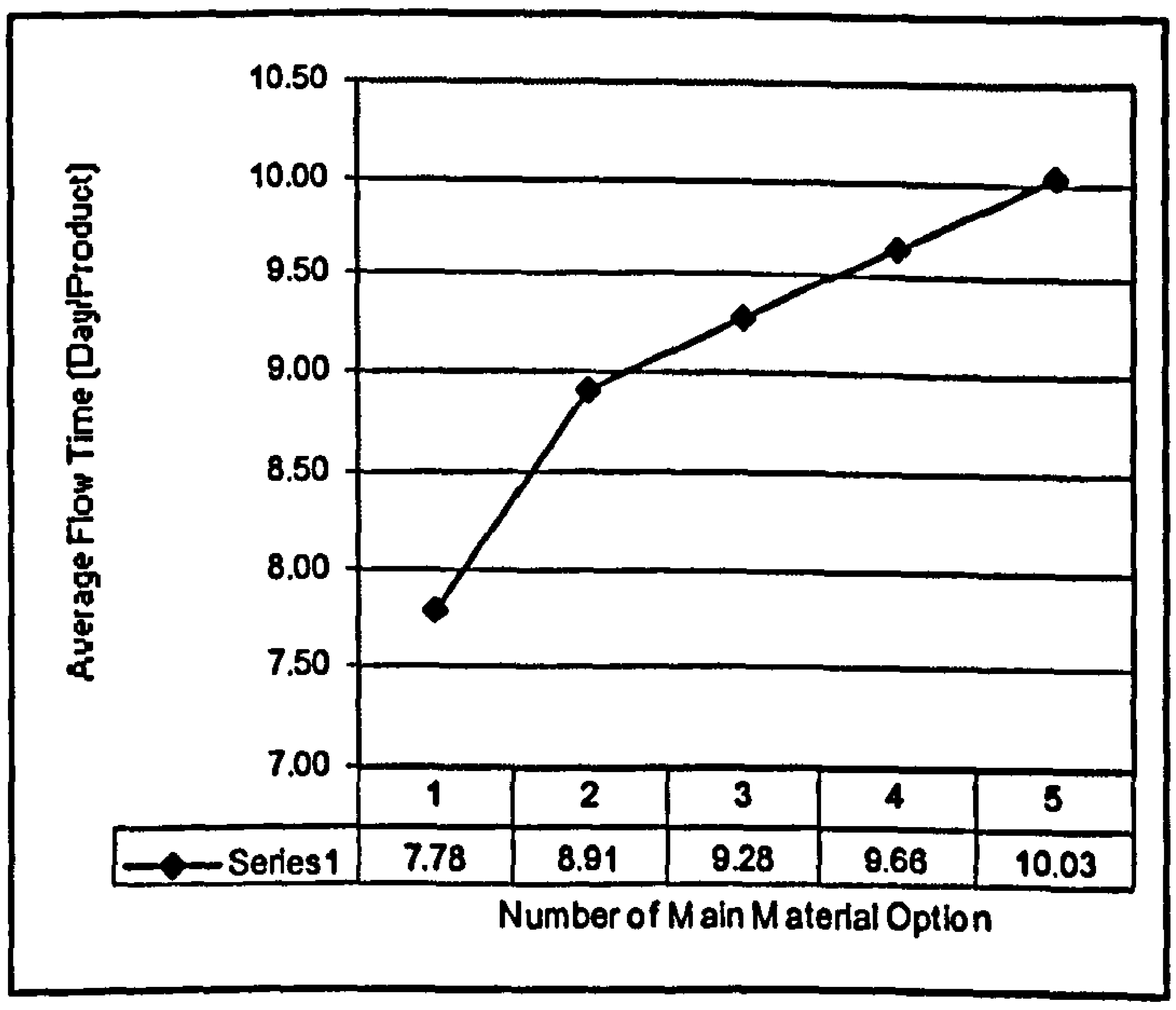


Figure A5.2 Average flow time when the number of main material options is increased

5.1.2 Verifying the mechanism for generating volume uncertainty

5.1.2.1 General differences of constant and variable demand

Another experiment was conducted to verify the mechanism to generate aggregate-level demand uncertainty. The number of main materials is three, while unique and packaging materials are set to one. Product-level demand is set to be constant and materials are bought from a local supplier. For illustrative purposes, the results of 20 measurement periods are summarised in table A5.7. The aggregate-level demand changes from one period to another with average of 16,400. The forecast is determined according to the formulas described previously. For example in period 5001, actual demand = 15,898, thus:

Forecast t+1 = 13,500 + 0.2 x 15,898 = 16,679

Forecast t+2 = 10,125 + 0.4 x 15,898 = 16,484

When all the errors over 10,000 measurement periods are considered, the average error is approximately equal to zero and standard deviation is approximately 3,372 (20% of average demand).

As the product-level demand is set to be constant, the proportion of each product variant should remain constant from one period to another. This is confirmed by the results shown in table A5.7, as the proportion of product 111, 121 and 131 is 33%, 33% and 33%, respectively over the simulation period. These results suggest that the mechanism to generate volume uncertainty is working as expected.

Table A5.7 Illustrative results of volume uncertainty when product-level demand is constant and suppliers are local

Month	Demand	For1	Error For1	For2	Error For2	% Prod. 111	% Prod. 121	% Prod. 131	Demand Prod. 111	Demand Prod. 121	Demand Prod. 131
5001	15898	16679		16484		33.33	33.33	33.34	5299	5299	5300
5002	16596	16819	-83	16763		33.33	33.33	33.33	5532	5532	5532
5003	16552	16810	-267	16745	68	33.33	33.33	33.34	5517	5517	5518
5004	10061	15512	-6749	14149	-6702	33.33	33.33	33.35	3353	3353	3355
5005	13398	16179	-2114	15484	-3347	33.33	33.33	33.33	4466	4466	4466
5006	17989	17097	1810	17320	3840	33.33	33.33	33.34	5996	5996	5997
5007	11408	15781	-5689	14688	-4076	33.33	33.33	33.35	3802	3802	3804
5008	10480	15596	-5301	14317	-6840	33.33	33.33	33.34	3493	3493	3494
5009	17417	16983	1821	17091	2729	33.33	33.33	33.34	5805	5805	5807
5010	23244	18148	6261	19422	8927	33.33	33.33	33.33	7748	7748	7748
5011	21883	17876	3735	18878	4792	33.33	33.33	33.34	7294	7294	7295
5012	17250	16950	-626	17025	-2172	33.33	33.33	33.33	5750	5750	5750
5013	18980	17296	2030	17717	102	33.33	33.33	33.34	6326	6326	6328
5014	14513	16402	-2783	15930	-2512	33.33	33.33	33.34	4837	4837	4839
5015	22531	18006	6129	19137	4814	33.33	33.33	33.34	7510	7510	7511
5016	18519	17203	513	17532	2589	33.33	33.33	33.33	6173	6173	6173
5017	19466	17393	2263	17911	329	33.33	33.33	33.34	6488	6488	6490
5018	16156	16731	-1237	16587	-1376	33.33	33.33	33.34	5385	5385	5386
5019	13888	16277	-2843	15680	-4023	33.33	33.33	33.34	4629	4629	4630
5020	11770	15854	-4507	14833	-4817	33.33	33.33	33.34	3923	3923	3924
Average	16400	16780	-402	16685	-426	33.33	33.33	33.34	5466	5466	5467
Std. Dev			3744		4362						

5.1.3 Verifying the mechanism for generating product mix uncertainty

In order to verify if the mechanism to generate product mix uncertainty is working as expected, an experiment was conducted with three different main material options, while the number of options for unique and packaging material are set to one. Aggregate-level demand is set to be constant and materials are bought from local suppliers. The results of 20 measurement periods are shown in table A5.8.

As shown in table A5.8, the average aggregate-level demand is 16,875 over the simulation periods. Forecasts for one period (For1) and two periods (For2) ahead is equal to the aggregate actual demand. As the main material options are increased to three, there are three different product variants with different proportion from one period to another. The average proportion of product 111, 121, 131 are 33%, 35% and 32% respectively. This confirms that the mechanism to generate product mix uncertainty is working as expected.

Table A5.8 Illustrative results of product mix uncertainty when aggregate-level demand is constant and suppliers are local

Month	Demand	For1	For2	% Prod. 111	% Prod. 121	% Prod. 131	Demand Prod. 111	Demand Prod. 121	Demand Prod. 131
5001	16875	16875	16875	32.81	32.62	34.58	5536	5504	5835
5002	16875	16875	16875	35.88	39.19	24.93	6054	6614	4207
5003	16875	16875	16875	26.22	30.31	43.48	4424	5114	7337
5004	16875	16875	16875	37.85	40.55	21.60	6388	6842	3645
5005	16875	16875	16875	32.27	34.10	33.62	5446	5755	5674
5006	16875	16875	16875	30.03	31.79	38.18	5068	5364	6443
5007	16875	16875	16875	25.46	35.00	39.53	4297	5907	6671
5008	16875	16875	16875	32.24	38.16	29.60	5441	6439	4995
5009	16875	16875	16875	32.32	35.98	31.70	5454	6071	5350
5010	16875	16875	16875	35.07	38.42	26.51	5918	6484	4473
5011	16875	16875	16875	36.33	29.34	34.33	6130	4951	5794
5012	16875	16875	16875	36.98	27.15	35.88	6240	4581	6054
5013	16875	16875	16875	34.42	34.26	31.32	5809	5781	5285
5014	16875	16875	16875	32.89	38.06	29.04	5551	6423	4901
5015	16875	16875	16875	28.58	30.67	40.75	4823	5176	6876
5016	16875	16875	16875	33.41	34.73	31.86	5638	5860	5377
5017	16875	16875	16875	32.96	41.56	25.48	5562	7013	4300
5018	16875	16875	16875	36.64	36.28	27.08	6183	6122	4570
5019	16875	16875	16875	33.22	35.98	30.80	5606	6072	5197
5020	16875	16875	16875	30.67	32.36	36.97	5176	5460	6239
Ave-rage	**16875**	**16875**	**16875**	**32.81**	**34.82**	**32.36**	**5537**	**5877**	**5461**

APPENDIX 6 IDENTIFICATION OF STEADY STATE

Eyeballing technique is used to identify the steady state. In addition to normal and most uncertain condition presented in chapter 5, the results shown in figure A6.1 – A6.4 are used in identifying the steady state period.

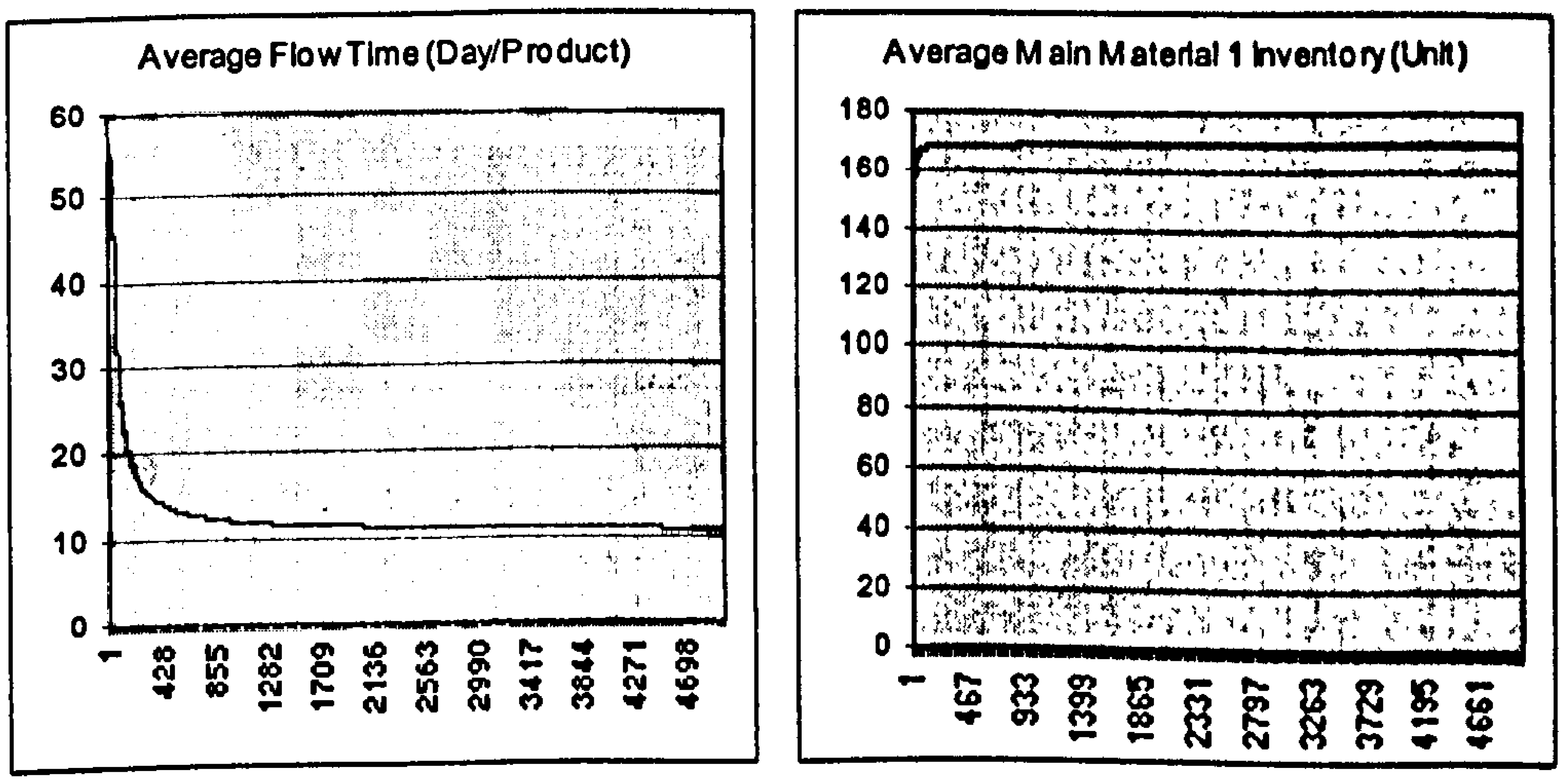


Figure A6.1 Average flow time (a) and average main material type 1 (b) when the system produces maximum variety while demand and supply remains constant

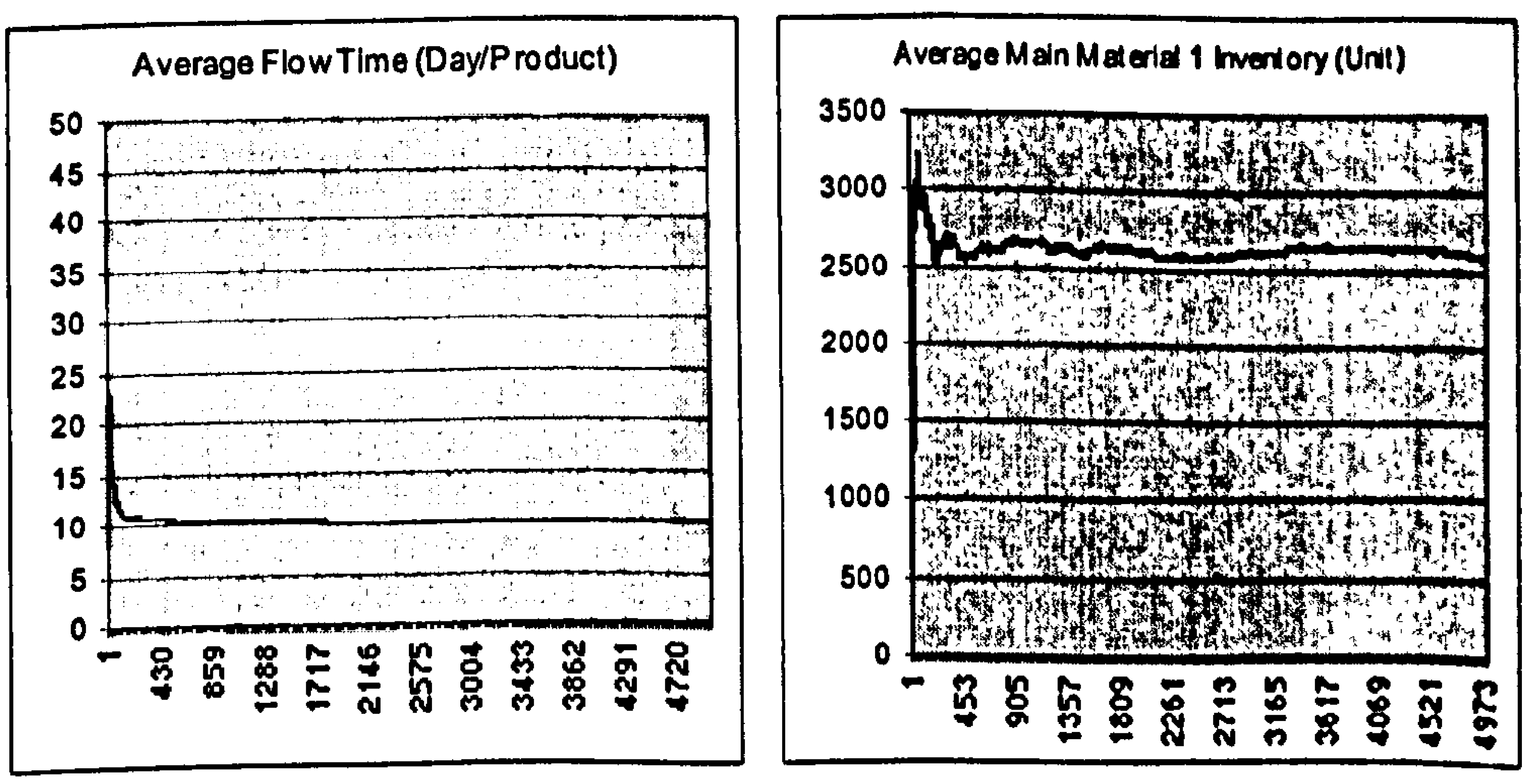


Figure A6.2 Average flow time (a) and average main material type 1 (b) when the system produces one type of product, demand is constant, suppliers of materials are local with variable delivery time

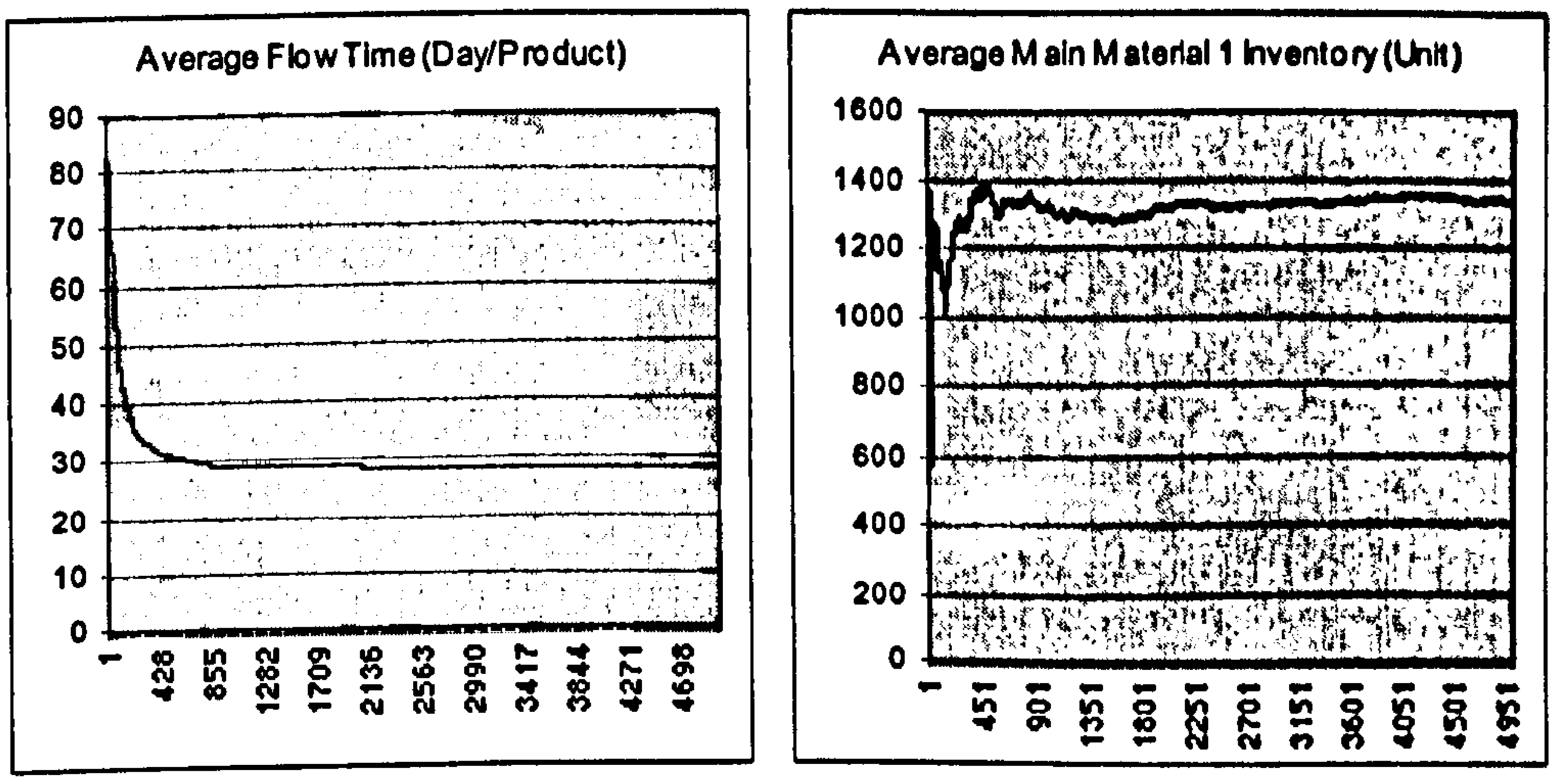


Figure A6.3 Average flow time (a) and average main material type 1 (b) when the number of main material option is 5, mix is uncertain, suppliers are global with variable delivery time

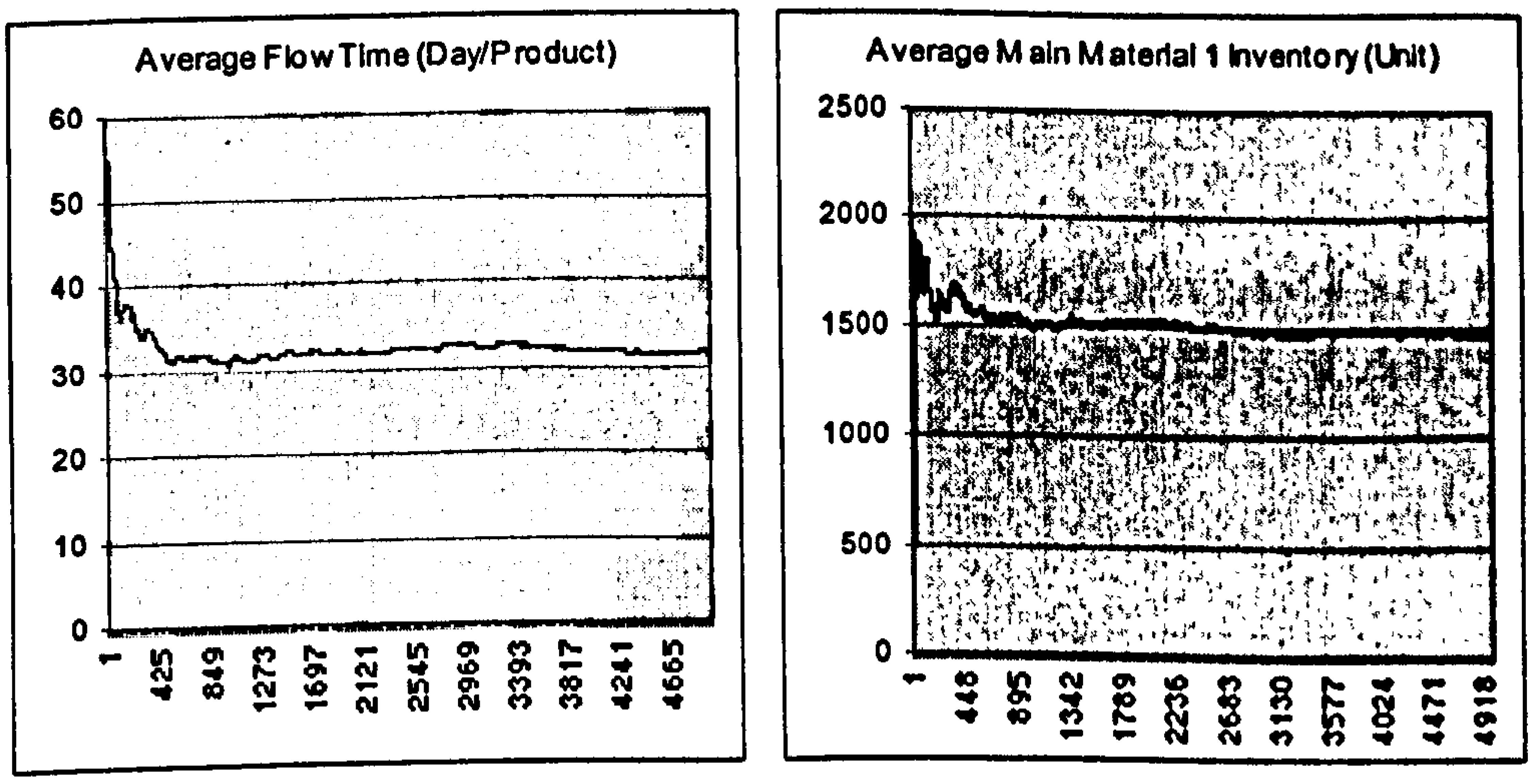


Figure A6.4 Average flow time (a) and average main material type 1 (b) when the number of main material options is 5, volume is uncertain, suppliers are global with variable delivery time

APPENDIX 7
RESULTS FROM EXPERIMENT INVESTIGATING THE IMPACT OF PRODUCT VARIETY, SUPPLY AND DEMAND UNCERTAINTY

Table A7.1. Results from mix uncertainty experiments with different levels of supply uncertainty for medium variety

Measure	Unit of Measurement	Mix Uncertainty & Local Suppliers							Mix Uncertainty & Global Suppliers						
		MM (Ex. 1)	UM (Ex.2)	PM (Ex.13)	MM UM (Ex.4)	MM PM (Ex.5)	UM PM (Ex.6)	MM, UM & PM (Ex.7)	MM (Ex. 8)	UM (Ex.9)	PM (Ex.10)	MM UM (Ex.11)	MM PM (Ex.12)	UM PM (Ex. 13)	MM, UM & PM (Ex.14)
Average Flow Time	(Day/Product)	12.61	10.63	9.55	13.71	12.65	11.17	13.52	17.65	14.09	12.18	20.54	18.99	16.28	21.00
Average Delay due to MM	(Day/Delayed Product)	8.42	0	0	8.42	6.95	0	6.95	12.94	0	0	12.99	11.63	0	11.613
Average Delay due to UM	(Day/Delayed Product)	0	7.51	0	4.83	0	6.29	4.21	0	12.86	0	9.75	0	11.40	8.81
Average Delay due to PM	(Day/Delayed Product)	0	0	7.50	0	5.86	6.16	5.70	0	0	12.89	0	11.13	11.71	10.57
Average Main Material Tardiness	(Day/Late Delivery)	5.00	0	0	5.00	4.99	0	4.99	14.92	0	0	14.92	14.99	0	14.99
Average Unique Material Tardiness	(Day/Late Delivery)	0	4.97	0	4.96	0	4.96	4.96	0	14.92	0	14.91	0	14.91	14.89
Average Packaging Mat. Tardiness	(Day/Late Delivery)	0	0	5.04	0	5.04	5.04	5.04	0	0	15.14	0	15.14	15.15	15.14
Average MM inventory	(Unit of Main Material)	4376	846	846	4386	3643	845	3640	7716	845	846	7747	6382	845	6365
Average UM inventory	(Unit of Unique Material)	846	4390	846	3650	846	3650	3241	846	7759	846	6425	846	6381	5807
Average PM Inventory	(Unit of Packaging Material)	846	846	4395	846	4395	4401	4400	846	845	7846	845	7786	7797	7829
Average System Inventory	(Unit of Material)	6067	6081	6086	8882	8883	8896	11281	9407	9450	9537	15018	15014	15024	20001

Table A7.2. Results from volume uncertainty experiments with different levels of supply uncertainty for medium variety

Measure	Unit of Measurement	Volume Uncertainty & Local Suppliers							Volume Uncertainty & Global Suppliers						
		MM (Ex. 15)	UM (Ex.16)	PM (Ex.17)	MM UM (Ex.18)	MM PM (Ex.19)	UM PM (Ex. 20)	MM, UM & PM (Ex.21)	MM (Ex. 22)	UM (Ex.23)	PM (Ex.24)	MM UM (Ex.25)	MM PM (Ex.26)	UM PM (Ex. 27)	MM, UM & PM (Ex.28)
Average Flow Time	(Day/Product)	15.92	12.39	11.65	16.38	16.08	12.80	16.71	20.70	15.81	14.05	22.61	21.92	17.79	23.74
Average Delay due to MM	(Day/Delayed Product)	8.25	19.00	19.00	8.22	8.26	19.00	8.23	12.74	19.00	19.00	12.66	12.75	19.00	12.60
Average Delay due to UM	(Day/Delayed Product)	4.34	6.54	0	5.13	4.41	6.50	5.10	4.93	11.64	0	9.90	5.07	11.58	9.90
Average Delay due to PM	(Day/Delayed Product)	0	0	6.54	2.80	4.16	4.12	3.87	0	0	11.63	4.15	9.73	9.98	8.96
Average Main Material Tardiness	(Day/Late Delivery)	4.99	0	0	4.99	4.99	0	4.99	14.94	0	0	14.94	14.94	0	14.94
Average Unique Material Tardiness	(Day/Late Delivery)	0	4.96	0	4.96	0	4.96	4.96	0	14.91	0	14.92	0	14.92	14.91
Average Packaging Mat. Tardiness	(Day/Late Delivery)	0	0	5.03	0	5.04	5.04	5.03	0	0	15.14	0	15.14	15.14	15.14
Average MM inventory	(Unit of Main Material)	4252	2932	2930	4253	4253	2953	4259	7282	2942	2915	7280	7244	2950	7309
Average UM inventory	(Unit of Unique Material)	2930	4253	2930	4252	2933	4278	4269	2922	7160	2915	7185	2936	7217	7220
Average PM Inventory	(Unit of Packaging Material)	2930	2932	4261	2926	4269	4287	4281	2922	2942	7308	2932	7333	7318	7354
Average System Inventory	(Unit of Material)	10112	10117	10121	11430	11455	11517	12809	13127	13045	13138	17397	17513	17484	21882

Table A7.3. Results from mix uncertainty experiments with different levels of supply uncertainty for high variety

Measure	Unit of Measurement	Mix Uncertainty & Local Suppliers							Mix Uncertainty & Global Suppliers						
		MM (Ex.29)	UM (Ex.30)	PM (Ex.31)	MM UM (Ex.32)	MM PM (Ex.33)	UM PM (Ex.34)	MM, UM & PM (Ex.35)	MM (Ex. 36)	UM (Ex.37)	PM (Ex.38)	MM UM (Ex.39)	MM PM (Ex.40)	UM PM (Ex. 41)	MM, UM & PM (Ex.42)
Average Flow Time	(Day/Product)	23.43	10.52	9.45	23.94	23.16	10.92	23.66	27.94	13.59	12.06	29.20	27.77	15.53	28.80
Average Delay due to MM	(Day/Delayed Product)	8.05	0	19.00	8.04	6.43	0	6.34	12.49	0	0.00	12.50	11.02	0	10.96
Average Delay due to UM	(Day/Delayed Product)	0	7.44	0	2.01	0	5.90	1.51	0	12.68	0	6.23	0	10.67	5.49
Average Delay due to PM	(Day/Delayed Product)	0	0	7.02	0	3.30	5.80	2.96	0	0	12.64	0	7.90	11.29	7.61
Average Main Material Tardiness	(Day/Late Delivery)	4.96	0	0	4.96	4.98	0	4.99	14.93	0	0	14.95	15.04	0	14.94
Average Unique Material Tardiness	(Day/Late Delivery)	0	5.01	0	4.99	0	5.00	5.00	0	15.00	0	15.06	0	15.02	14.97
Average Packaging Mat. Tardiness	(Day/Late Delivery)	0	0	5.01	0	5.01	5.02	5.04	0	0	15.08	0	15.04	15.03	15.08
Average MM inventory	(Unit of Main Material)	4271	845	845	4265	3423	845	3359	7557	846	846	7533	6021	846	5962
Average UM inventory	(Unit of Unique Material)	846	4291	845	3421	846	3416	3008	846	7561	846	6051	846	6045	5473
Average PM Inventory	(Unit of Packaging Material)	846	845	4269	846	4264	4260	4213	846	846	7550	846	7500	7489	7431
Average System Inventory	(Unit of Material)	5962	5982	5960	8532	8533	8522	10579	9248	9253	9241	14430	14367	14380	18865

Table A7.4. Results from volume uncertainty experiments with different levels of supply uncertainty for high variety

Measure	Unit of Measurement	Volume Uncertainty & Local Suppliers							Volume Uncertainty & Global Suppliers						
		MM (Ex.43)	UM (Ex.44)	PM (Ex.45)	MM UM (Ex.46)	MM PM (Ex.47)	UM PM (Ex.48)	MM, UM & PM (Ex.49)	MM (Ex.50)	UM (Ex.51)	PM (Ex.52)	MM UM (Ex.53)	MM PM (Ex.54)	UM PM (Ex.55)	MM, UM & PM (Ex.56)
Average Flow Time	(Day/Product)	26.86	12.66	11.74	27.12	26.37	13.03	27.40	32.90	15.66	14.09	33.84	32.73	17.76	34.31
Average Delay due to MM	(Day/Delayed Product)	8.34	19.00	19.00	8.32	8.33	19.00	8.33	12.67	19.00	19.00	12.70	12.67	19.00	12.65
Average Delay due to UM	(Day/Delayed Product)	3.48	6.98	0	4.19	3.63	6.91	4.30	3.79	11.85	0	8.32	3.96	11.83	8.32
Average Delay due to PM	(Day/Delayed Product)	0	0	7.02	2.48	3.64	3.94	3.30	0	0	11.88	3.28	8.41	9.94	7.64
Average Main Material Tardiness	(Day/Late Delivery)	4.99	4.99	0	4.99	4.99	0	5.00	14.90	0.00	0	15.00	14.96	0	14.97
Average Unique Material Tardiness	(Day/Late Delivery)	0	0.00	0	5.00	0	4.99	5.02	0	14.93	0	14.96	0	15.01	15.03
Average Packaging Mat. Tardiness	(Day/Late Delivery)	0	0	5.00	0	5.01	5.00	5.04	0	0	15.09	0	15.06	15.11	15.11
Average MM inventory	(Unit of Main Material)	4343	2937	2932	4336	4349	2921	4346	7396	2942	2915	7358	7386	2922	7399
Average UM inventory	(Unit of Unique Material)	2940	4351	2932	4347	2950	4337	4354	2933	7300	2915	7279	2955	7234	7314
Average PM Inventory	(Unit of Packaging Material)	2940	2937	4340	2931	4354	4328	4355	2933	2942	7316	2931	7385	7350	7388
Average System Inventory	(Unit of Material)	10223	10225	10204	11614	11653	11587	13055	13262	13184	13147	17568	17726	17506	22100

APPENDIX 8 WORST CASE ANALYSIS

The worst case analysis aims to show the worst situation that supply chains producing high variety in highly uncertain demand and supply have to cope with. While most of the experiments conducted in this study concentrated on the average values of key performance measures, the worst case analysis particularly aims to capture variability of the supply chain performance.

Simulation results reported in chapters 6 – 9 demonstrate that the supply chain shows worst performance when it produces maximum variety (125 different product variants), buys all materials from global suppliers and aggregate level demand (volume) is subject to uncertainty. Therefore, this situation is considered in the worst case analysis. In this situation, as already explained in Chapter 5, no minimum batch size is imposed.

Similar to the previous experiments, the first 5,000 periods are discarded to ensure that the system has reached a steady state. This is followed by 5,000 measurement periods, where two main measures, flow time and inventory level, are collected. However, in addition to the average values, additional statistics to capture the variability of the performance measure are also collected. Unlike in the previous experiments where the average flow time is weighted by the batch size (number of unit in a batch) as shown in equation 5.1, for the purpose of the worst case analysis the average flow time is measured per batch in order to capture the extreme values.

- **Inventory**

Figure A8.1 shows the minimum, average and maximum inventory level for each material stock. It is obvious that in a high variety and high uncertainty situation the maximum level of inventory that the system has to carry can be very high. As shown in figure 1, the minimum level of each material option is zero. On the other hand, the maximum level of each material option is in the range of 11,000 to 14,000 units of material. The graph also shows that the average inventory levels are much closer to the associated minimum values than the maximum values. This indicates that the inventory often sit at their maximum levels for a relatively short time. This is true because it is often the case that once a large number of materials arrives from the supplier, it is immediately deployed to the production system.

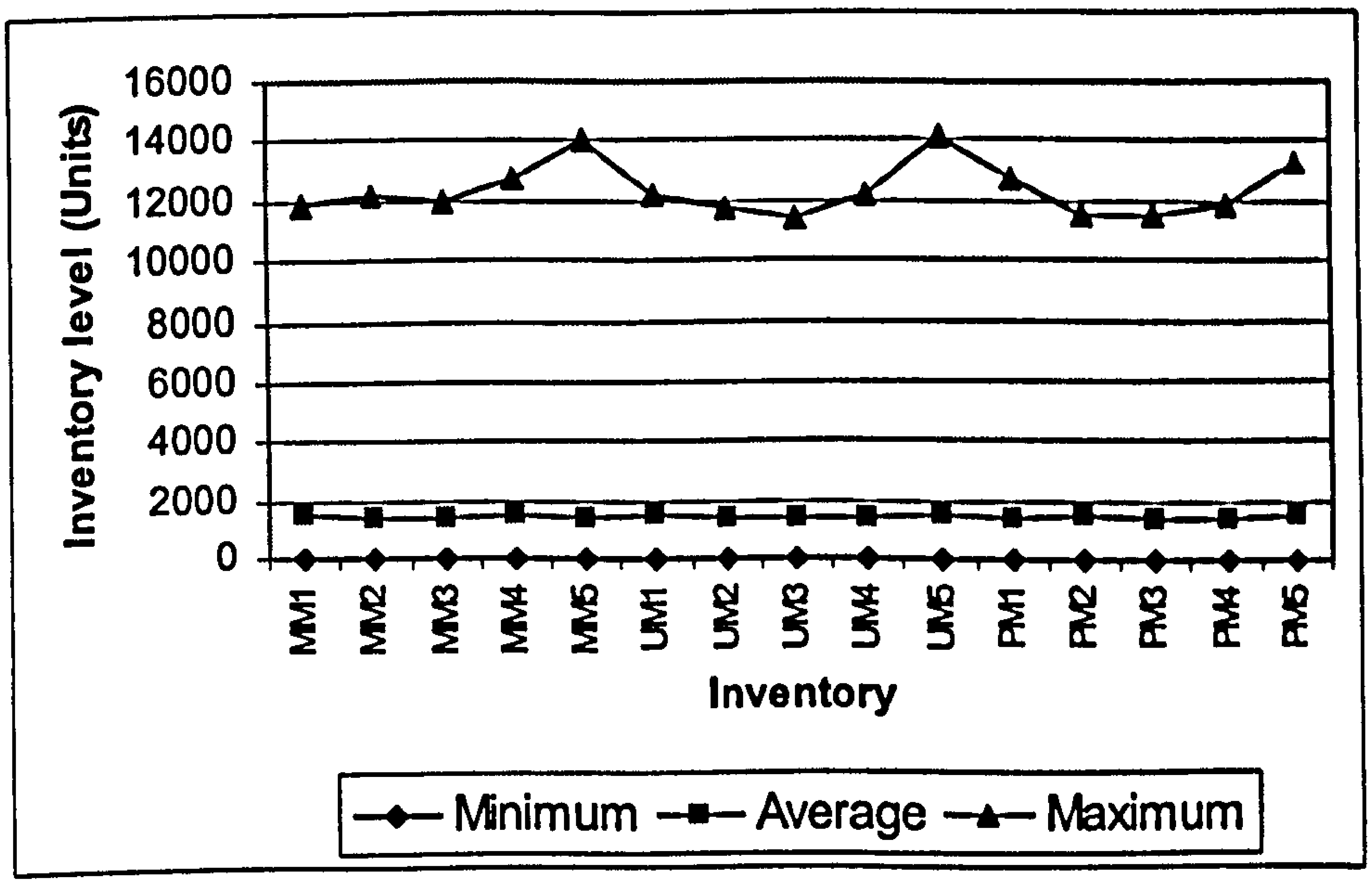


Figure A8.1 Range of inventory level

- Flow Time

Summary of descriptive statistics associated with flow time is presented in table A8.1. The overall results suggest that in the most uncertain situation, the flow time per batch has a relatively high variability. The average flow time per batch is 33.91 day with a standard deviation of 14.51 days. The results also suggest that the minimum flow time is 0.49 day, which is approximately 2 standard deviation below the average. In contrast, there is also a case that a batch can only be finished in 117.82 days. This worst case is almost 6 standard deviation above the average value. However, there are only about 1% cases with a flow time above 3 standard deviation.

Table A8.1 Descriptive statistic

Measure	**Unit of measure**	**Results**
Number of sample	Batch	625,084
Average flow time	Day/Batch	33.91
Standard Deviation of flow time	Day	14.51
Minimum flow time	Day	0.49
Maximum flow time	Day	117.82
Percentile 25^{th}	Day	24.06
Percentile 50^{th}	Day	32.82
Percentile 75^{th}	Day	42.19

Frequency distribution of flow time is shown in figure A8.2. The 25^{th}, 50^{th} and 75^{th} percentile are 24.06, 32.82 and 42.19 days respectively. This means that for upper 75^{th} quartile there is a range flow time of 42.19 – 117.82 days with an average of 52.81 days. This means that although these extreme values rarely happen, they reflect the great risks associated with producing maximum variety when demand and supply are subject to uncertainty. If such situation happens, the supply chain may face serious consequences in terms of losing customer confidence and losing future orders.

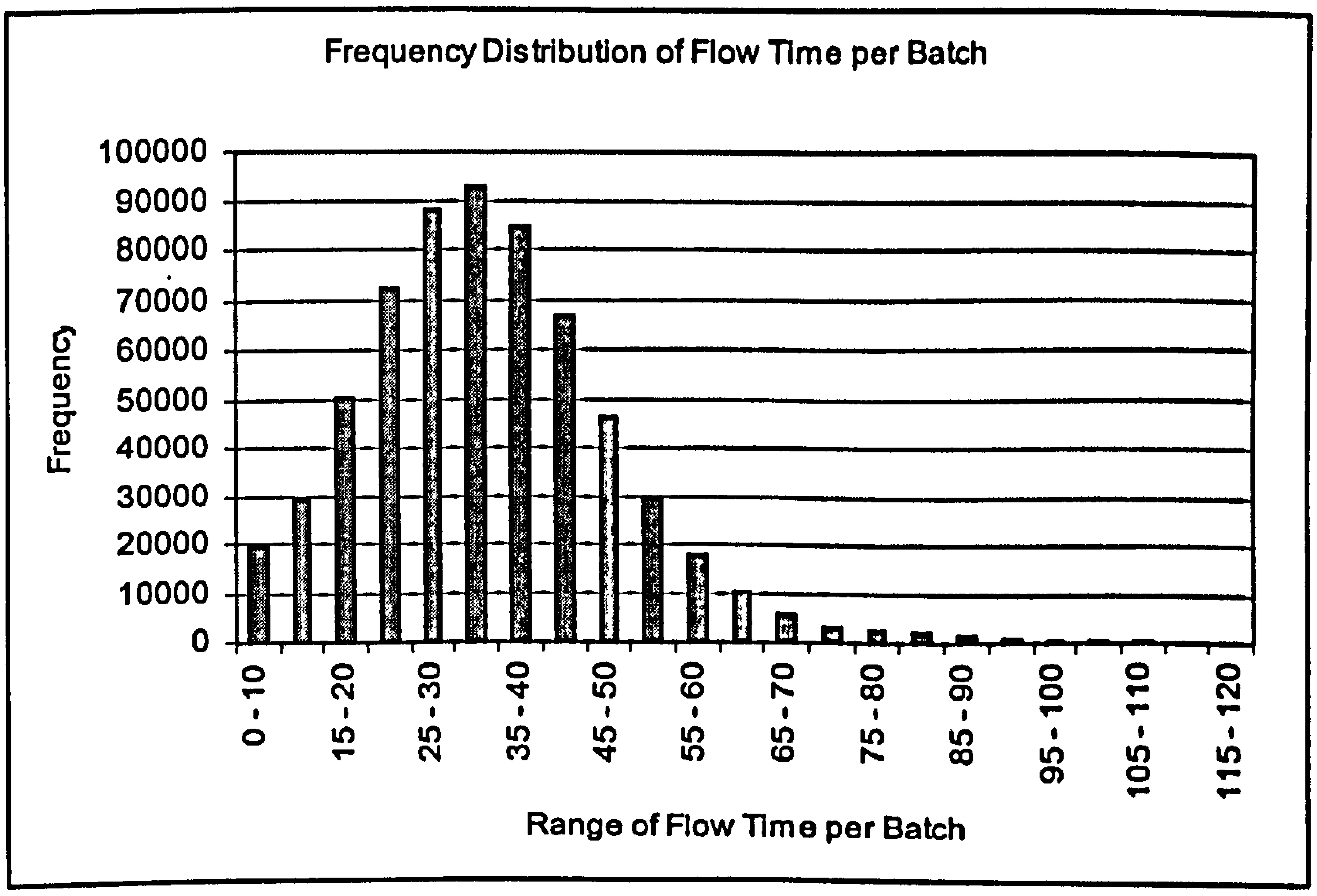


Figure A8.2 Frequency distribution of flow time per batch

- Batch size Vs. Flow time

Further analysis is conducted to investigate the variability of flow time for different batch sizes. The results for the first 62,500 batches are examined to develop a frequency distribution of batch sizes (figure A8.3) and minimum and maximum flow time for different class of batch sizes (table A8.2 and figure A8.4).

Figure A8.3 shows the frequency distribution of the batch size. The figure indicates that there is significant variability in batch sizes. The descriptive statistical analysis reveals that the average batch size is 134 units, but the actual batch could be as small as 51 units and could be as large as 270 units. This variability can be understood, as we did not impose any minimum quantity for a batch to start a production when the system produces maximum variety.

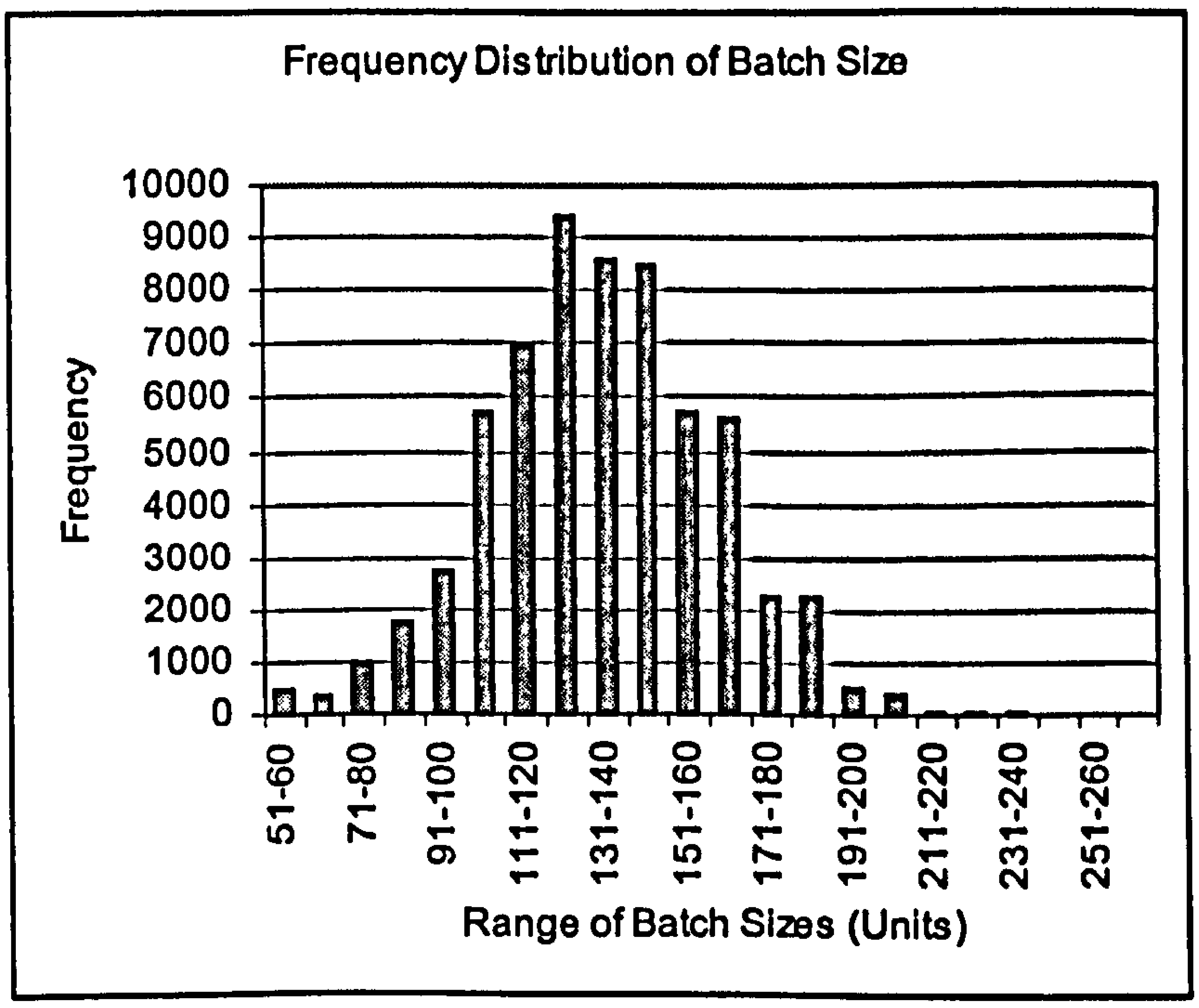


Figure A8.3 Frequency distribution of batch size

Table A8.2 presents the mean, minimum and maximum flow time for each class of batch size. Figure A8.4 shows that the minimum flow time increases slightly with the batch size. However, the increases are not so evident for the maximum flow time. This indicates that even a small batch size could have a very long flow time. For example, a batch with 71 – 80 units could take up to 78 days to finish. This is understandable because the flow time is not only determined by the batch size i.e. processing time, but also by the availability of materials to produce the batch. When the materials required to produce a batch is not available at the right amount at the right time, these batches may have to wait for a long period of time. Again, this is not a favourable performance for the supply chain. Despite conducting production without a minimum batch size, which reflects a relatively flexible manufacturing system, there is still a chance that smaller batch takes a long time to finish due to other inefficiencies: delays due to material shortages, queue time and set-up time.

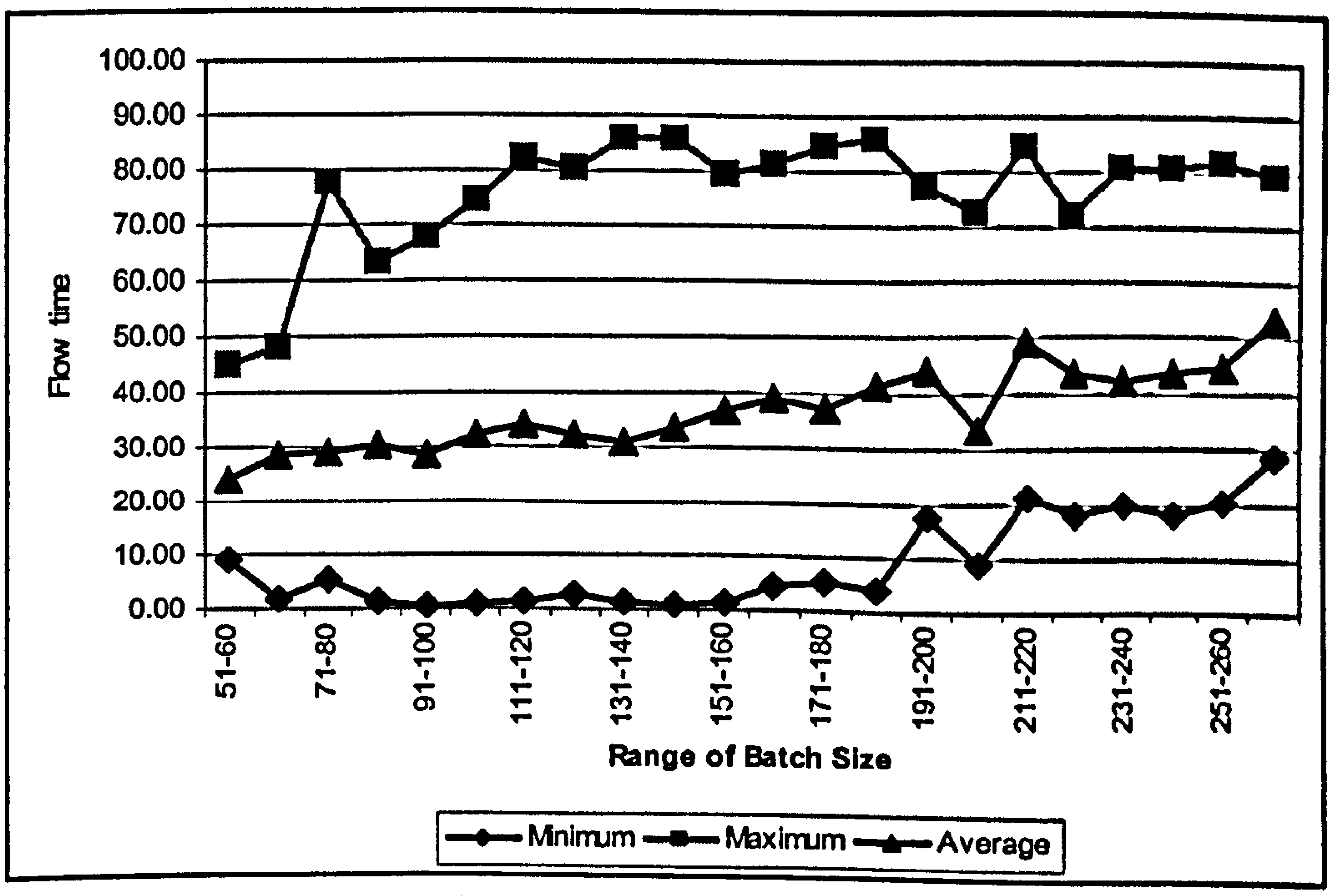


Figure A8.4 Range of flow time for different classes of batch size

Table A8.2 Minimum, maximum and average flow time for different batch sizes

Range of Batch Size	Min	Max	Average
51-60	9.03	44.81	23.97
61-70	1.84	48.09	28.52
71-80	5.42	77.54	29.27
81-90	1.22	62.96	30.25
91-100	0.49	67.59	28.84
101-110	1.10	74.52	32.38
111-120	1.28	82.36	34.10
121-130	2.51	80.67	32.49
131-140	1.31	85.82	31.07
141-150	0.69	85.86	33.74
151-160	1.34	79.34	36.81
161-170	4.71	81.40	39.16
171-180	5.49	84.34	37.29
181-190	3.98	85.73	41.57
191-200	17.87	77.50	43.95
201-210	9.09	72.79	33.43
211-220	21.16	84.50	49.11
221-230	18.26	72.48	43.82
231-240	20.20	80.86	42.35
241-250	18.26	80.86	43.85
251-260	20.44	81.60	44.58
261-270	28.70	79.55	53.16

The worst case analysis indicates that in a high product variety and highly uncertain supply and demand, the supply chain facing great risks due to the possibility of a very long lead-time to finish a batch (up to 6 standard deviation above the average value) and high level of inventory. Despite a very few occurrences of these extreme cases, the supply chain needs to be aware of such risks in order to mitigate their negative impacts when such situation occur, and more importantly to avoid their occurrences. These can be done by applying several strategies or combination of strategies proposed in chapter 9: structural-based, product-based, process-based, co-ordination-based and responsiveness strategies.