# Modelling, Simulation, and Analysis of Supply Chain Systems Using Discrete-Event Simulation

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# Abstract

Many approaches have been developed which support the construction of detailed supply chain models useful for analysis and simulation. However, most of these approaches lack the ability to model the supply chain in a single model, and usually produce solutions that lead to conflicting strategies between the companies. Simulation using a discrete-event simulation (DES) is an effective tool for the dynamically changing supply chain variables, thus allowing the system to be modelled more realistically. Considering the complexities of the supply chain system and the interrelations between its various systems, the task of developing such a model is challenging. The aim of this thesis is to develop a simulation model of a fast moving consumer goods (FMCG) supply chain with a DES tool. This model would be utilised as a decision-support system (DSS) for the investigation of the effectiveness of several inventory policies towards effective coordination and control of production-inventory system, in various situations.

This thesis discusses fundamental issues in the development of a simulation model for a supply chain using the DES tool, ARENA. A modelling procedure for the development of a supply chain simulation model is presented. The overall structure of the model is constructed by incorporating the well documented concept of modelling materials flowing downstream with an approach of modelling orders flowing upstream (modelling of feedback information). The model has an easily adaptable structure where rules (inventory policies) and model variables can be modified. The flexibility in the model's structure allows devising appropriate experimental designs, for several tests to be performed to imitate some realistic situations or scenarios (including the presence of disturbances). A new control theory oriented inventory policy, called the pseudo PID, is proposed. Detailed evaluations of five inventory policies for a production-inventory control under dynamic and stochastic conditions is presented. The findings demonstrate the ability of the approach to provide a wealth of potential solutions to the decision-maker, and confirm the qualitative behaviour of a supply chain in response to the different policies.

# Publications

The results presented in this work have/would appeared in the following publications:

1. N. Saad, S. Bennett, and V. Kadirkamanathan. "Modelling supply chain dynamics with a discrete-event simulation". Proceedings of the Second IASTED International Conference on Artificial Intelligence and Applications, AIA 2002, Malaga, Spain, 9th – 12th September 2002.

2. N. Saad, " Modelling, Simulation and Analysis of a FMCG Supply Chain Dynamics". Proceedings of the United Kingdom Automatic Control Council UKACC Conference, Control 2002 Postgraduate Symposium, Sheffield, United Kingdom, 10th September 2002.

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4. C.E. Riddalls, N. Saad, and S. Bennett, " The Control of Inventory Systems Incorporating Quantity Discounts". Proceedings of the European Control Conference, ECC 2001, Porto, Portugal, 4th-7th September 2001.

5. N. Saad, V. Kadirkamanathan and S. Bennett " A discrete-event simulation model for analysis of supply chain dynamics", Computers in Industry, Elsevier Science, (submitted - May 2003).

# Table of Contents

**Acknowledgements** i
**Abstract** ii
**List of Publications** iii
**Table of Contents** iv
**List of Figures** vii
**List of Tables** ix
**List of Abbreviations** xi
**Nomenclature** xii

**Chapter 1 Introduction**

1.1 Background 1
1.2 Motivation 2
1.3 Objectives and contribution of the research 3
1.4 Outline of the thesis 7

**Chapter 2 Background to Supply Chain Problems**

2.1 Introduction 9
2.2 Production planning and scheduling 10
2.3 Approaches to controlling supply chain operations 13
2.3.1 MRP/MRP II 13
2.3.2 JIT 16
2.3.3 JIT with Kanbans 18
2.3.4 Lean supply/ enterprise 20
2.4 Approaches to analysis and design of supply chain systems 23
2.4.1 Continuous time differential equations models 23
2.4.2 Discrete time difference equations models 24
2.4.3 Classical operational research techniques 25
2.4.4 Discrete-event dynamic systems (DES) simulation models 26
2.4.5 Agent-based modelling approach 26
2.5 Related research work on modelling supply chains 28
2.6 Modelling issues 32
2.7 Control strategies 33
2.7.1 Optimisation 33
2.7.2 Centralised control 35
2.7.3 Distributed/decentralised control 35
2.8 Summary 36

## Chapter 3 Discrete-Event Simulation (DES) Modelling of a Supply Chain System


3.1 Introduction 38
3.2 Introduction to discrete-event simulation (DES) 39
3.2.1 Modelling schemes in DES 40
3.2.1.1 The event scheduling scheme 40
3.2.1.2 The process-oriented simulation scheme 41
3.2.2 Examples of DES languages 44
3.3 Developing a simulation model 46
3.4 The supply chain system 48
3.4.1 System description 49
3.4.2 Problem formulation (the model description) 51
3.4.3 The study objectives 56
3.5 Modelling issues 57
3.5.1 Minimum details for modelling a supply chain 57
3.5.2 Modelling a supply chain with DES 58
3.6 The conceptual model 60
3.6.1 Define system's behaviour explicitly 60
3.6.2 Develop system's inputs and outputs explicitly 61
3.6.3 Mechanism for coordinating entities flow 62
3.6.4 Modularity approach for 'scalability' and reducing model complexity. 63
3.6.5 Sequence diagrams 64
3.7 The implementation model 71
3.7.1 The general system's requirements 73
3.7.2 The interactions of information 74
3.7.2.1 Modelling flow of messages 75
3.7.3 The tracking and controlling of systems entities. 77
3.8 Summary 78


## Chapter 4 Model Verification and Validation


4.1 Introduction 79
4.2 Model verification 80
4.2.1 Programming tracing for Base model. 80
4.2.2 Programming implementation model using ARENA 84
4.3 Model validation 85
4.3.1 Model validation: Comparisons of simulation results to calculations of systems equation 86
4.4 Simulation example 95
4,5 Summary 101


## Chapter 5 Performance Analysis of Policies in Base model


5.1 Introduction 103
5.2 Supply chain performance measures 104
5.3 Supply chain inventory models 108
5.3.1 Generic policy 108
5.3.2 *(s,S)* policy 108
5.3.3 Smooth average policy 109
5.3.4 Pseudo PID policy 109
5.3.5 Vendor-managed inventory (VMI) policy 110

5.4 Problem formulation 111
5.4.1 The Base model description 111
5.4.2 Description of policies implemented at packer/filler company 113
5.4.3 Description of the model performance measures and objectives 116
5.5 Description of the Test Model 120
5.6 Experiments 123
5.6.1 The first Test model: Pulse input 124
5.6.2 The second Test model: Step input 126
5.6.3 The third Test model: Sinusoidal input 128
5.6.4 The fourth Test model: Random input 131
5.7 Results and analysis 133
5.8 Summary 139

**Chapter 6 Contextual Load Model**

6.1 Introduction 140
6.2 Contextual load model design 142
6.3 The sources of disturbances 145
6.4 Modelling the disturbances 147
6.4.1 Type I disturbance: Change in product demands 148
6.4.2 Type II disturbance: Manufacturing capacity disturbances 148
6.4.3 Type III disturbance: Inventory disturbance 149
6.5 Modelling disturbance routines 151
6.6 Simulation results and analysis 159
6.6.1 The simulation example 1: Type I disturbance – Changes in product demand 159
6.6.2 The simulation example 2: Type II disturbance – Manufacturing capacity 161
6.6.3 The simulation example 3: Type III disturbance – Inventory disturbances 163
6.6.3.1 Type III-Faulty material: Part 1- 'One-off' situation 163
6.6.3.2 Type III-Faulty material: Part 2- Random simulation 165
6.6.3.3 Type III-Late delivery 168
6.7 Overall summary of results 172
6.8 Summary 173

**Chapter 7 Conclusions and Future Work**

7.1 Conclusions 174
7.2 Directions for future work 177

**References** 179

**APPENDICES**

**Appendix I** Percentage points of the *t* distribution 190

# List of Figures


| | | |
|---|---|---|
| **Figure 3-1** | A flow chart representation of the modelling steps. | 48 |
| **Figure 3-2** | A schematic diagram of the FMCG supply chain. | 50 |
| **Figure 3-3** | A description of the interactions between companies and their internal structures. | 51 |
| **Figure 3-4** | Sequence diagram for the retailer and the packer/filler companies. | 68 |
| **Figure 3-5** | Sequence diagram for the packer/filler and printer companies. | 69 |
| **Figure 3-6** | Sequence diagram for the printer, the blanks supplier and the raw material supplier companies. | 70 |
| **Figure 3-7** | A process chart representation of the implementation model. | 72 |
| **Figure 4-1** | A process chart used in the verification process. | 81 |
| **Figure 4-2** | Schematic diagram for the basic system equations. | 88 |
| **Figure 4-3** | Production rates and inventory levels. | 98 |
| **Figure 4-4** | Inventory levels at each company, the blank label manufacturer, the label printer, and the packer/filler. | 99 |
| **Figure 5-1** | Patterns for retailer orders. | 117 |
| **Figure 5-2** | The supply chain configuration: cases for implementing the generic policy, $(s,S)$ policy, smooth average policy, and pseudo PID policy. | 121 |
| **Figure 5-3** | The supply chain configuration: case for implementing the vendor-managed inventory policy. | 122 |

| | | |
|---|---|---|
| **Figure 5-4** | Production rates and inventory levels of the system with Pseudo PID policy (at packer/filler) in response to a pulse change in retailer's demand. | 124 |
| **Figure 5-5** | Production rates and inventory levels of the system with Smooth average policy (at packer/filler) in response to a step change in retailer's demand. | 126 |
| **Figure 5-6** | Production rates and inventory levels of the system with (*s,S*) policy (at packer/filler) in response to a sinusoidal change in retailer's demand. | 129 |
| **Figure 5-7** | Production rates and inventory levels of the system with VMI policy (at printer) in response to a random change in retailer's demand. | 131 |
| **Figure 5-8** | The effect of long period of negative growth in retailer's order on the Packer/filler's inventory. | 136 |
| **Figure 5-9** | Effect of inventory policy on stock level at the packer/filler, to illustrate the response time. | 137 |
| **Figure 6-1** | General conceptual framework for the supply chain system. | 143 |
| **Figure 6-2** | Functional layout of a packaging industry supply chain. | 144 |
| **Figure 6-3** | The control system structure of the packaging industry supply chain system. | 146 |
| **Figure 6-4** | Sample paths for retailer's ordering pattern. | 153 |
| **Figure 6-5** | Sample paths for machine breakdown. | 154 |
| **Figure 6-6** | Sample paths for packer/filler printed labels stock. | 156 |
| **Figure 6-7** | Sample paths for late delivery. | 158 |
| **Figure 6-8** | *t* Distribution for $n$=4 Degrees of Freedom and the location of $T$=0.6703. | 167 |
| **Figure 6-9** | Risk of stock-outs and the number of undelivered batch for a specified duration of late deliveries. | 170 |

# List of Tables


| | | |
|---|---|---|
| **Table 3-1** | The main notation | 49 |
| **Table 3-2** | Parameter values for base model | 55 |
| **Table 3-3** | Simulation markers nomenclature. | 67 |
| **Table 4-1** | Program tracing: The sub-model representations as derived from conceptual model description. | 82 |
| **Table 4-2** | Tabulation of sample calculations for data validation as produced in simulation for Base model, $d$=7 to 22. | 94 |
| **Table 4-3** | Ordering, production, and inventory records at each company, from day 1 to day 60. | 97 |
| **Table 5-1** | Performance measures and objectives for a supply chain system. | 105 |
| **Table 5-2** | Test models, ordering policies and the respective mathematical equations | 115 |
| **Table 5-3** | Performance measures, descriptions, and objectives for the model. | 120 |
| **Table 5-4** | Comparison on the effectiveness of implementing the ordering decision (policy) based on the performance metrics (For each case, the system is subjected to a similar pulse input) | 125 |
| **Table 5-5** | Comparison on the effectiveness of implementing the ordering decision (policy) based on the performance metrics. (For each case, the system is subjected to a similar step input) | 128 |
| **Table 5-6** | Comparison on the effectiveness of implementing the ordering decision (policy) based on the performance metrics. (For each case, the system is subjected to a similar sinusoidal input) | 130 |
| **Table 5-7** | Comparison on the effectiveness of implementing the ordering decision (policy) based on the performance metrics. (For each case, the system is subjected to a similar random input) | 133 |

| | | |
|---|---|---|
| **Table 5-8** | Average stock level, average variation in order quantity set to printer, and downstream demand amplification indices for generic, (*s,S*), smooth average, pseudo PID and VMI decision policies at packer/filler. | 135 |
| **Table 6-1** | Disturbances type and the sources of disturbances. | 147 |
| **Table 6-2** | Models for the simulation of disturbances | 150 |
| **Table 6-3** | Comparison on the effectiveness of the decision (policy) in the presence of variations in the input pattern, based on the performance metrics. | 160 |
| **Table 6-4a** | Comparison on the effectiveness of the decision (policy) in the presence of disturbance (machine breakdown occurs before regular order is made), based on the performance metrics. | 162 |
| **Table 6-4b** | Comparison on the effectiveness of the decision (policy) in the presence of disturbance (machine breakdown occur after regular order is made), based on the performance metrics. | 162 |
| **Table 6-5a** | Comparison on the effectiveness of the decision (policy) in the presence of disturbance (faulty materials), based on the performance metrics. | 164 |
| **Table 6-5b** | Samples of average inventory level at packer/filler for different random input demand pattern from retailer | 165 |
| **Table 6-6** | Comparison on the effectiveness of the decision (policy) in the presence of disturbance (late deliveries, duration of 4 days), based on the performance metrics. | 169 |

# List of Abbreviations

| | |
|---|---|
| **C-kanban** | Conveyance Kanban |
| **DES** | Discrete-Event Simulation |
| **DSS** | Decision-Support System |
| **EDI** | Electronic Data Interchange |
| **FMCG** | Fast Moving Consumer Goods |
| **JIT** | Just-in-time |
| **MRP/MRPII** | Manufacturing Resource Planning |
| **OR** | Operational Research |
| **P-kanban** | Production Kanban |
| **VMI** | Vendor-managed Inventory |
| **WIP** | Work-in-process |

# Nomencluture

### *Notation*

| | |
|---|---|
| $x$ | Subscript indicating company $x$={A \|B \| C \| D \| E } |
| $i$ | Day of the week index ($i=0$ indicates Sunday), $i$=0,...,6 |
| $w$ | Week number index, $w$= 0, 1,...,$W$ |
| $d$ | Day number index (numbering starts from start of simulation) $d=(7w+i)$ or, $d$=0,1,...,$D$ |
| $E$ | Number of emergency orders set to printer |
| $e$ | Size of emergency order sent to printer |
| $I_x(d)$ | Inventory level of printed labels at company $x$ on day $d$ |
| $p_x(d)$ | Production at company $x$ on day $d$ |
| $S_x$ | Order-up-to-level for company $x$ |
| $s_x$ | Re-order level for company $x$ |
| $ss_x$ | Minimum stock level for company $x$ |
| $u_x(d)$ | Order placed by company $x$ on day $d$ |
| $V_D(w)$ | Average variation in weekly orders placed by company D measured at week $w$ |
| $y_x(d)$ | Goods delivered by company $x$ on day $d$ |

### *Math operators*

| | |
|---|---|
| / | Division |
| * | Multiplication |
| - | Subtraction |
| + | Addition |

### *Logical operators*

| | |
|---|---|
| .eq., = | Equality comparison |
| .ge., ≥ | Greater than or equal to comparison |
| .gt., > | Greater than comparison |
| .le., ≤ | Less than or equal to comparison |
| .lt., < | Less than comparison |
| .ne., ≠ | Not Equal to comparison |

# Chapter 1

# Introduction

## 1.1 Background

Supply chain management is seen as being an important element of the *Next Generation Manufacturing Enterprises*. Supply chain management is a very broad area that encompasses important topics such as inventory management, logistic network design, distribution systems, strategic alliances, value of information in the supply chain, information technology and decision-support systems, and international issues in supply chain management. A supply chain is an " *integrated process wherein a number of various business entities (i.e., suppliers, manufacturers, distributors, and retailers) work together in an effort to: (1) acquire raw materials, (2) convert these raw materials into specified final products, and (3) deliver these final products to retailers*", [Beamon 98].

The analysis and design of a supply chain system requires both static and dynamic information from different parts of a company. The static data may include plant production rates, plant locations, warehouses, and customers as well as warehousing and transportation costs. The dynamic data may include forecasts, orders, and current deliveries. Providing rapid and quality responses to supply chain events requires the co-ordination of multiple functions across the enterprise. In order to produce an efficient, well co-ordinated enterprises, there must be timely dissemination of information, accurate co-ordination of decisions and management of actions among people and systems along the chains. Nevertheless, the dynamics of the enterprise and the market make this difficult. Unpredictable occurrences of events such as suppliers providing incorrect materials or late delivery, failing of production facilities, absent workers, or customers making changes to or cancelling orders , etc., can be recognised as disturbances to the system, causing deviations from the plan. The systems have to quickly respond to market dynamics while minimising lead times and inventory. Hence, it is important that the system be able to co-ordinate the revision of the plan across the supply chain functions.

The research in supply chain management can be dated back to just before the 1960's. Most of the research works reported in the literature have a strong business management and operations research (OR) emphasis. Its associations to the research works in OR, particularly, in the area of production scheduling is recognizable. Interest in supply chain management, both in industry and academia has grown rapidly since 1980, with a dramatic increase in the publication rate since 1990. Not surprisingly, different research communities have begun to address different aspects of the problem, bringing to bear a variety of different research traditions, problem perspectives, and analytical techniques. The economic advantage of studying and improving the issues related to supply chain is considerable.

Generally, there are four distinct methodologies with which the supply chain has been modelled, namely: continuous time differential equations models, discrete time difference equations models, classical operational research (OR) approach, and discrete-event dynamic simulation (DES) models. Detailed reviews of the modelling methods used to model and analyse supply chain described above, and a summary of the important issues arising in supply chain research, may be found in Riddalls *et. al.*, [RiddBT 99] and [RiddBT 00], and Beamon, [Beamon 98]. In addition to the above approaches, there is an emerging concept from the field of computer science that is being used to attack the problem of modelling and analysing supply chains, namely the agent-based modelling approach. One defining attribute about agent-based modelling is the ease of translating back the model behaviour into practice. Agent-based modelling approach allows on-line intelligent agents (software processes) to use artificial intelligence, in this case a database of rules collected from human experts, to assist in decision-making, especially for real-time decisions, such as determining how to supply a customer in the shortest possible time, or what quantity to produce at a particular facility, etc., see for example Fox *et. al.* [FoxBarTe00] and Parunak *et. al.* [ParuSaRi 98].

## 1.2 Motivation

Due to shortened product life cycles, rising manufacturing costs, and the globalisation of market economies, increasing attention has been placed on supply chain management. The need to simulate and redesign supply chain processes to allow

decision makers to explore various options and scenarios that are customer and value driven has been recognised, [Hennesse 98]. Simulation has been identified as one of the best means to analyse a supply chain [SchunkP 00]. Although many companies are involved in the analysis of their supply chain, still, in most cases the analysis is performed based on experience and intuition, and not many analytical models and design tools have been used in the process [SimKS 00]. A number of commercial supply chain simulation tools have become available in recent years, for example in Barnett and Miller [BarnettM 00], and Phelps *et. al.* [PhelpsPS 00]. More often, these software packages can be useful for very quick analysis of a model, but have limited capability to conduct a detailed simulation.

The position within the academic community is very different. Many methods have been developed which support the construction of detailed models useful for analysis and simulation. However, these have largely been used to investigate optimisation of a small segment of the supply chain, for example, machine scheduling in a job-shop or in a flow-shop. The need to optimise the performance of the whole supply chain connecting raw material to finished product, by controlling the transmission of schedule instability and the resulting inventory fluctuation is often overlooked. Another important issue is that most of the current approaches lack the ability to model the supply chain in a single model, and usually produce solutions that lead to conflicting strategies between the companies. Motivated by this noticeable inadequacy, this research aims to find answers to integration and co-ordination questions such as this through computer modelling via the discrete-event dynamic simulation tool, ARENA. Considering the complexity of the supply chain where different stages in the system may have different conflicting goals and objectives, the task of developing such a model is significant and challenging.

## 1.3 Objectives and contribution of the research

One of the significant aspects of the supply chain management is the control and coordination of production-inventory decisions. The inventories exist in the supply chain in several forms for example, raw material inventory, work-in-process (WIP) inventory, and finished product inventory. Their primary purpose is to buffer against any uncertainty that might exist in the supply chain. The control policies such as the

determination of the optimal levels of order quantities and reorder points, and setting safety stock levels is important since they are the primary determinants of customer service levels. Each of these needs its own control mechanism. The difficulty in determining these mechanisms is that efficient production, distribution, and inventory control strategies that reduce system-wide costs and improve service levels must take into account the interactions of the various levels in the supply chain. The main issue covered in this research is the investigation of the effectiveness of several inventory policies towards effective co-ordination and control of production-inventory system in a supply chain, in various situations. The model for the study is derived from analysis of a packaging industry supply chain. A detailed description of the supply chain system used for this study is given in Chapter 3.

Evidently, the OR and classical control theory approaches have dealt successfully with many production-inventory scheduling problems especially when they are static and deterministic in nature. The OR approach has been used to provide local solutions to limited problems for example, scheduling, calculation of optimum batch size, etc. The control theory approach is dynamical, but it relies heavily on linearity assumptions that are not satisfied in most supply networks. Such solutions may lead to conflicting strategies between echelons (companies). For that reason, it is *necessary to view the supply chain as comprising of supplier, manufacturer, distributor, and retailer in one model so that it can be analysed as a single integrated process* rather than as a sequence of independent entities. See [FoxBarTe 00], [OttaBurn 00], [ParuSaRi 98], [SaHiKjTs 99], and [SwaSmSa 98] for examples.

In a paper, Riddalls, Bennett, and Tipi [RiddBeTi 99] compare the effectiveness of four approaches for supply chain analysis, namely, continuous time differential equation models, discrete time difference equation models, DES tools, and OR techniques. They concluded that while OR techniques are useful in providing solutions to local tactical problems, the impact of these solutions on the *global behaviour of the whole supply chain can only be assessed using dynamic simulation.*

The recent availability of DES has made it possible to treat the supply chain system as one large complex system. A DES approach can show the supply chain as comprising of supplier, manufacturer, distributor, and retailer in one model so that it

can be analysed as a single integrated process rather than as a sequence of independent entities. This simulation approach will enable a model to be expanded as required to capture the dynamics of the real system. The defining attribute of DES models is their ability to capture the discrete nature of events-based processes, whilst retaining a continuous time framework. It allows different combinations of decision strategies to be evaluated, that is, by enabling the programmer (modeller) to include some fixed rules or expert system based rules directly into the model.

The way a DES simulation works have been outlined by many authors, including Banks *et. al.*, [BanksCN 96]. The DES is the modelling of systems in which the state variable changes only at a discrete set of points in time. In principle, such a simulation model can be made to mimic the detailed operation of the system under study, through a computer program that effectively steps through each event, that would occur in the system. The simulation models are analysed by numerical methods by employing computational procedures to 'solve' mathematical models. An artificial history of the system is generated based on the model assumptions, and observations are collected to be analysed and to estimate the true system performance measures.

Considering that most of the research results are difficult to implement in the real world, a suitable modelling approach that is able to transform the descriptions of a system's behaviour under analysis into a computer model and then allows transcribe back some important aspects of the models into task descriptions is needed. Another defining attribute about DES modelling is that it allows *the transformation of system's behaviour descriptions into a computer model, while also allowing the translation back of the model's behaviour into practice.* To allow the modelling of a supply chain system to include the important aspects relevant to the study objectives such as dynamic behaviour over time, and how the system responds to external events is significant.

DES simulation tools, for example ARENA, were originally designed for use in simulating manufacturing systems, and are a very useful approach in evaluating resource flows (such as machinery, people, and materials). The modelling usually requires the tracking and controlling of the flow of system entities through several

stages of production facilities, and normally these entities are transformed into new products (parts) as they undergo various processes.

In modelling a supply chain, there is a vital requirement to model the arrival of orders or messages (upstream flow of orders or messages), which shall be regarded as a feedback process. However, the modelling of orders (messages) has rarely been addressed due to the fact that a DES tool is intended for use in attacking a direct process oriented problem that is similar to the manufacturing system. Hence, the task of formulating such an approach is challenging.

The main contributions of this research are that, this thesis,

- **Presents an approach for modelling a supply chain with a DES tool**. The modelling involves two main features: the modelling of resource flows, and the modelling of orders (messages) being dispatched between the companies. As the overall structure of the model is developed based on modelling of manufacturing systems, the modelling of orders is carried out by systematically correlating the logical and mathematical relations and the dynamics of the message between the physical components in the system.

- **Builds a simulation model for a packaging industry supply chain**. As an experimental tool for the evaluation and re-designing of decision policies, the simulation model is useful for providing information and is a guide for a decision-maker in finding solutions that are more accurate and credible. The model is built by defining a set of objects (resources and entities) to describe the behaviour of the system, driven by a set of processes (logical and mathematical relationships) leading to the accumulation of output data such as production sizes and inventory levels, for analysis and interpretation.

- **Investigates the effectiveness of several ordering policies.** As orders from a downstream echelon have significant effects on the behaviour of the upstream echelon, a number of ordering policies are investigated and their influences are compared. Qualitative behaviour of supply chain to different policies confirmed through detailed quantitative analysis.

- **Proposes an inventory policy, referred to as 'pseudo PID'**. The unique feature of this policy is its similarity to the PID controller developed by viewing the supply chain as a feedback control system.

- **Builds a contextual load model.** It is important to analyse the effectiveness of the ordering policies in the presence of dynamic disturbances. The model is built by defining a set of objects (resources and entities) to describe the behaviour of the system, governed by a set of processes (logical and mathematical interconnections), incorporated with a set of contextual loads (changes in product demands, changes in machine capacity, etc.) affecting the system's performance, leading to the collection of output data such as inventory levels, for analysis and interpretation.

## 1.4 Thesis Overview

This thesis basically consists of two parts. Part I (Chapters 1 & 2) presents an introduction to supply chains and highlights the importance of the approach used in this work, gives review and finally sets the scene for the research work. Part II (Chapters 3~6) presents the design approach to developing a simulation model for a supply chain using discrete-event simulation (DES), including conceptual modelling, model implementation, model verification and validation, and the experimental design and illustrations with some application examples. The detailed outline of the thesis is as follows:

Chapter 2 presents a survey of the current practices in controlling supply chain operation, the methods of modelling and analysing a supply chain, and a review of the research work related to the modelling of supply chain dynamics. The drawback of the common approaches (analytical and mathematical approach) in modelling a dynamic system is discussed, and the potential of utilising a DES for solving a supply chain problem is elucidated. A discussion on the current control strategies on designing a supply chain network is presented. The last section of this chapter summarises the shortcoming of most of the related work in this area and finally sets the scene for the research work reported in this thesis.

Chapter 3 describes the modelling approach undertaken to produce a computer simulation model of a supply chain system using a discrete-event simulation (DES) language. This includes an explanation on the design of a conceptual model of the supply chain system, and the design and development of an implementation model based on the conceptual model associated with ARENA simulation language.

Chapter 4 discusses the verification and the validation processes taken to illustrate that the simulation model performs as expected and intended and established that the model behaviour validly represents that of the system being simulated.

Chapter 5 gives examples to illustrate the application of the simulation model in evaluating the effectiveness of several supply chain policies. The simulation model is used to test out several decision policies that have been formulated based on observation of real-life processes, where the performances of each case is compared and analysed.

Chapter 6 continues the modelling that has been developed in the previous three chapters (Chapters 3 ~ 5) where additional design requirements are to be introduced. The purpose is to answer several issues particularly on whether the decision policies (inventory policies) used would provide stability under the presence of disturbances, as well as evaluating the effect of disturbances on the process (the supply chain system). Several tests have been devised, and several aspects of performance measures are considered.

Finally, Chapter 7 gives the conclusions of this thesis and suggests future research directions relevant to simulation and modelling of supply chains.

# Chapter 2

# Background to Supply Chain Problems

## 2.1 Introduction

A supply chain is a thread of operation in a complex network of enterprises with possibly different conflicting goals and objectives. It is a set of activities which span enterprise functions from the ordering and receipt of raw materials through the manufacturing of products through distribution and delivery to the customer. The basic purpose is to satisfy the end customer. In order to operate efficiently, these functions must operate in an integrated manner.

Basically, the supply chain management functions operate on three levels: strategic level, tactical level, and operational level. Each level is distinguished by the period of time over which decisions are made, and the granularity of decisions during that period. The strategic level addresses issues such as where to allocate production, and what is the best sourcing strategy. The tactical level addresses issues such as forecasting, scheduling, ordering of short lead-time materials, and scheduling over time to meet production requirements. The operations level addresses issues such as inventory deployment, detailed scheduling, and what to do with an order when a machine breaks down. The ability to analyse and understand effectively the many aspects of the supply chain system is important for effective decision-making. The suitability of the analysis tool to use depends on the requirement and the level of detail the solution requires.

The layout of this survey is as follows:
Section 2.2 provides a general discussion to production planning and scheduling. Section 2.3 gives a representation survey of current practices in controlling supply chain operation. Section 2.4 examines the various methods of modelling and analysing a supply chain. A review on the research work related to the modelling of supply chain dynamics using the analytical modelling and simulation modelling is presented in Section 2.5. Section 2.6 highlights the issues of modelling a dynamic system and the potential of utilising a DES for solving a supply chain problem. Section 2.7 discusses the current control strategies on designing a supply chain network and gives an overview of the co-ordination control of supply chain planning processes. Finally, Section 2.8 sets the scene for the research work reported in this thesis.

## 2.2 Production planning and scheduling

Due to the multi-disciplinary nature of this research, and its relationship with production planning and scheduling, the inclusion of a discussion on the production planning and scheduling in this review is considered important to help in understanding the issues in supply chain research.

Bitran and Tirupati [BitrTi 93] define production as the process of converting raw materials into finished products. Manufacturing systems are typically composed of large numbers of components, which have to be managed effectively in order to deliver the final products in right quantities, on time and at appropriate cost. In systems characterised by multiple products, production management encompasses a large number of decisions that affect several organisation echelons.

In order to better understand production decisions in a manufacturing company, three categories of decisions have been defined, that is, strategic planning, tactical planning and operations control. Bitran and Tirupati [BitrTi 93] have proposed the following definitions:

- Strategic planning decisions are mostly concerned with the establishment of managerial policies and the development of resources to satisfy external requirements in a manner that is consistent with the organisational goals. In the area of production management these decisions relate to the design of production facilities and include the following: (1)

location and sizing of new plants, (2) acquisition of new equipment, (3) selection of new product lines, and (4) design of logistic systems.

- Tactical planning focuses on the resource utilisation process. At this stage, after decisions have been made regarding physical facilities, the basic problem to be solved is the allocation of resources such as capacity, workforce availability, storage and distribution resources. Typical decisions in this category include utilisation of regular and overtime labour, allocation of capacity to product families, accumulation of seasonal inventories, definition of distribution channels, and selection of transportation activities. These decisions involve a medium-range planning horizon, and the aggregation of items into product families. Models addressing these issues are classified as aggregate planning models.

- Operations control deal with day-to-day operational and scheduling problems, which require complete disaggregation of the information generated at higher levels. Typical decisions at this level include the following: (1) production sequencing and lot sizing at the item level, (2) assignment of customer orders to individual machines, (3) inventory accounting and inventory control activities, (4) dispatching, expediting and processing orders, and (5) vehicles scheduling.

Detailed examples of integrated production planning and scheduling are given in Bitran and Hax ([BitrHa 77], [BitrHa 82]), Bitran, Haas and Hax ([BiTrHaHa 81], [BitrHaHa 82]), and Joseph and McClain [JoseMc 93].

Production planning is the process of determining a tentative plan for how much production will occur in the next several time periods of interval of times called the planning horizon. Production planning also determines expected inventory levels, as well as the workforce and other resources necessary to implement the production plans. This is done using an aggregate view of the production facility, and the demand for products for the next few months. The planning system uses aggregate production information, like holding and set-up costs, capacity, lead-time, horizon and orders, and generates a production plan which meets aggregate demand due dates by performing an overall aggregate production cost minimisation.

Production scheduling is a more detailed process than production planning: coupling individual products with individual production resources using smaller time units or even continuous time. The objective of production scheduling is to find a way to assign and sequence the use of these shared resources such that production constraints are satisfied and production costs are minimised [FredWhit 88]. Often, despite its greater detail, a production schedule typically cannot be implemented exactly. Unpredictable occurrences of events such as machine breakdowns, worker absences, new rush orders, and other disruptions impose last minute changes to the schedule. In real-time, implementation of a production plan or schedule is often called dispatching. This shows the schedule as an ordered, daily list of the jobs to be done, their priority and routing through the machines, and the process time, and even the records on inventory and bill of materials. These decisions are an important part of the operation of a productive facility. They must keep the production plan on track, and feedback of the actual current situation helps the next plan to be achievable.

In the production management literature, production planning and scheduling decisions are viewed as two levels of decisions, see for example Joseph and McClain [JoseMc 93]. While aiming at managing production so that the right items in the right quantities are produced and delivered on time, these decisions are mainly concerned with costs reduction and effective resources utilisation. Initially, the upper level planning system will produce a medium-term production plan, before it feeds the lower scheduling system with information and constraints, like a set of lots or jobs to be produced within their fixed due dates. In order to build a short-term plan, the lower level scheduling system uses detailed production information, like processing times and set-up times of individual jobs and the availability time of individual machines. The scheduling system produces a detailed production plan for the shop floor, which is devoted to implementation and, therefore, tackles only the first period of the planning horizon. The information gathered on the shop floor state during the implementation of the schedule, like inventory levels and capacity availability, is sent back to the scheduling and planning systems. The scheduling plan might be rebuilt using feedback information from the shop floor like machines breakdown, arrival of urgent orders and shortages of raw materials. The planning system is rerun regularly in a rolling horizon basis after being fed back by new incoming demands, information concerning the implementation of previous plans, estimation of available resource capacities and inventory levels.

One important observation is that the aggregate available capacity considered at the planning level could be overestimated or underestimated. Capacity is the maximum amount of a product that can be made within a specified time. Capacity overestimation results in an infeasible plan, or unpredictable delays at the scheduling level. The company will not be able to meet all the demand and results in dissatisfied customers. On the contrary, capacity underestimation results in the wastage of capacity, leading to constitution of larger inventories or to backlogging. Since backlogging costs can be very high, one easy strategy leads to the constitution of a safety stock of end-items as well as an increase in work in process inventories. In spite of the fact that this high inventory level leads to a better response to customer demand, it generates higher costs and under-used resources.

It is important to note that a good integration and interaction of the two levels, planning and scheduling, are required for an effective capacity utilisation. This integration is better carried out when the scheduling system feeds back the planning system with accurate information about the capacity utilisation at its level. Numerous discussions relating to this issue have been reported.

Detailed discussion on the various approaches used for controlling the supply chain operations is given in the next section.

## 2.3 Approaches to controlling of supply chain operations

A representative survey of current practices in controlling supply chain operation systems is provided in this section. An extensive study on MRP, and JIT is given in Graves *et.al.* [GravRiZi 93]. For more background on the influences of the approaches such as JIT, lean production on the organization of supply chains and assessment of the impact of changes on SMEs see [Anon 96].

### 2.3.1 MRP (Material Requirements Planning) / MRP II (Material Resource Planning)

MRP originated in the USA as a computerized approach for the planning of materials acquisition and of production. MRP is a dependent inventory system, where stocks are matched directly to production plans. As MRP is highly dependent on computers and need

links to several systems, organizations have only really been able to use MRP since the early 1970s. Since then it has been widely adopted in manufacturing industry.

One of the main reasons that MRP was adopted so quickly as the production management technique was that it made use of the computer's ability to store information centrally and provide access to a detailed amount of information, for example, the immediate feedback of sales data sufficient to run a company. It gives the facility to coordinate the activities of various functions in the manufacturing firms such as engineering, production and materials. Another relevant aspect that makes MRP more viable is the implementation of Electronic Data Interchange (EDI). EDI plays an important role in facilitating the interconnection of the MRP system of one company with those of its suppliers. This has two purposes: to shorten the purchasing cycle and to transfer appropriate information for longer range material and capacity planning back to suppliers.

The next major extension to MRP is Manufacturing Resource Planning (MRP II). By the early 1980s organizations realized that the MRP approach of exploding a master production schedule to find material needs could be extended to other functions such as dispatching, distribution, production processes, and even marketing and finance. The aim of MRP II was to give an integrated system, with all parts linked back to a production plan. Eventually, the master production schedule could form the basis for planning most of the resources used in a process.

Detailed explanations about MRP/MRP II functionality are given in Vollman *et. al.* [VollBeWh 97] and Browne *et.al.* [BrowHaSh 90]. Also, literature review for MRP and MRP II can be found in Ip and Yam [IpYa 98], Yusuf and Little [YusuLi 98], and Braglia and Petroni [BragPe 99].

MRP works approximately as follows. Initially, tactical planning takes the strategic plans and expands these to give master production schedules. In the next stages of planning, organizations add more details to the master production schedules, to give more detailed operational schedules. MRP then expands the master production schedule to develop timetables for the supply of materials. For a fixed planning horizon, MRP systems determine: (1) the quantities of which item that will be used in the production of a prescribed volume of end products, and (2) the times at which each of these items must be

purchased or manufactured to meet prescribed due dates for the end products. First, for each end product the quantities of all components and sub-assemblies which are used in the manufacture of that product are determined. Using prescribed processing times and working backwards from the date for final assembly, MRP next determines the latest time at which these components and subassemblies should be made or ordered. Finally, MRP performs a more detailed capacity requirements analysis, determines an operation sequence, and sizes production lots.

The difference between MRP and the traditional independent demand system is the pattern of material stocks. With MRP, stocks are generally low but rise as orders are delivered just before production starts. The stock is then used during production and declines to its normal, low level. With independent demand systems, the stocks are not related to production plans, and most times have to be kept high. Stocks are reduced during production, but then will be replenished as soon as possible.

An MRP system is a highly detailed and an excellent means for determining and tracking materials requirements. The MRP analyses can provide early warning of potential problems and shortages. If necessary, expediting can be used to speed up deliveries, or production plans can be changed. In this way, MRP generally improves the wider performance of the organization, measured in terms of equipment utilization, productivity, customer service, response to market conditions, and so on. The main benefit of MRP is its ability to match the supply of materials to known demands. This reduces stock levels and associated costs.

More specifically, MRP is a 'push' system, where jobs are released to the first stage of manufacturing, and in turn this stage pushes the work in progress to the succeeding stage and so on, until the final products are obtained. The main shortcoming of this system is that customer demand must be forecast and production lead times must be estimated. In a 'push' system, production decisions are based on long-term forecasts [Artm 95]. Bad forecasts or estimates result in excess inventory, and the longer the lead time, the more inaccurate forecasts due to an increased forecast horizon. As the actual installed or available production capacity is ignored, MRP schedules could unrealistically prescribe machine loadings in excess of 100-percent utilization. Production volumes and due dates must be adjusted manually to achieve feasible schedules. A second shortcoming of MRP is

that it is entirely deterministic and cannot anticipate the impact on schedules of variable processing times and random events.

### 2.3.2 JIT (Just-in-time)

In the past few years, organizations have given a lot of attention to just-in-time (JIT), see for example Cook and Roowski [CookR 96], Ehrhardt [Ehrhardt 98] and Kim and Takeda [KimT 96]. JIT, developed in Japan, has become an effective approach to gaining competitive advantage in manufacturing. JIT production is a scheduling approach that dictates reduced material inventories and minimum WIP inventories to aid process improvement and reduce process variability. This approach, which integrates and manages manufacturing activities, obviously leads to cost efficiency and to consistently high product quality. Its lean inventories also allow rapid response to the changing needs of the marketplace.

JIT attempts to achieve high-volume production using minimal inventories of parts that arrive just in time. The general approach is to produce or deliver small batches of items in the precise amounts needed by subsequent production processes, or customers, at exactly the time needed. In general, JIT is a 'pull' system, in which a production process pulls materials from a prior process in support of the final assembly schedule, which is closely coordinated with customer demand, see for example Krajewski and Ritzman [KrajRi 87].

Generally, the JIT approach for production control is most applicable where production requirements are known and fixed far in advance and where buffering is not required to smooth the unavoidable effects of process time variations. This point is illustrated by the material flow associated with flexible manufacturing systems, job shops, or any other system where a variety of parts with wide variations in process times share the same resources. For example, the JIT approach works best in applications such as the assembly process for products with predictable sales such as refrigerators, automobiles, etc. The uncertainties in these applications are not high enough to require intermediate buffering in order to achieve the maximum production rate possible. In other words, JIT can only be used in certain types of organization. In particular, it needs a stable environment, constant rate of production, small batches, short lead times, and so on.

Many firms have been successful in using JIT to integrate and manage their internal operations and even to coordinate their operations with those of their suppliers, but difficulties often arise at the interface with the marketplace. While promoters of JIT emphasize the advantages of reducing inventories to zero, some theories and many practitioners recognize that some inventories are desirable, see for example Zangli [Zang 87]. This is especially likely when certain aspects of the system are unavoidably random for example, the demand for finished goods, which is often unmanageable and random. For this reason, many firms still maintain a buffer inventory of finished goods.

The obvious benefit of JIT schedules is the reduced capital cost associated with holding inventories, both in terms of reduced inventory storage requirements and reduced investment in raw materials and intermediate goods on hand. The more subtle benefits are associated with the improvements in process flow, particularly with respect to the early detection of rejects and immediate isolation of the associated undesirable operation.

An analysis on JIT suitability as an approach for a supply chain system is given in Bennett and Riddalls [BennRi 00]. The use of JIT introduces real-time (on-line) feedback into the system. The "request for supply" can be thought of as an error signal, it represents the difference between what is available and what is required: in a similar way "an order" in a supply chain can be viewed as a feedback signal. The use of real-time information from elsewhere in the chain, whether it is feedback from the retail end of the chain or feed-forward from the raw material end of the chain, is of benefit only if it can be used to modify (control) some aspect of the operation of the chain. The introduction of JIT at the downstream end of the chain has often revealed that production rates upstream cannot be easily controlled and the only available form of control in the chain has been manipulation of inventory levels. Thus meeting the JIT requirements at the downstream end has often simply resulted in transferring the costs of holding inventory upstream.

In highlighting the above issue, Bennett and Riddalls [BennRi 00] give the following example. Company A requires a JIT supply from company B with a four hour lead time. Company B has a minimum production time of eight hours and the materials it requires from Company C are delivered in a minimum quantity which represents one months supply. The adoption of JIT by A reduces that company's inventory level but does not reduce the

overall costs in the chain. It may not actually reduce company A's cost since the costs of handling small deliveries may be greater than savings resulting from reducing inventory.

As a scheduling approach, the success of JIT production demands highly reliable suppliers, workforce, and repair facilities, since buffer stocks are essentially eliminated. JIT realizes that co-operation is more productive than conflict. However, JIT has the disadvantage that it is purely descriptive. JIT is an approach that needs a complete change of attitudes and operations within an organization. It is likely to take several years of careful planning and controlled implementation to introduce it successfully. Another disadvantage is the high risks of interrupted production due to low inventories.

Successful implementations of JIT have been described and discussed by many authors, including Schroeder [Schr 00]. The first and most successful application of JIT system was at the Toyota Motor Company in Japan. In 1980, Kawasaki U.S.A. in Nebraska started implementation of JIT. Implementation has been achieved in many other U.S. companies, including Ford, General Electric, General Motors, Motorola, Black & Decker, Hewlett-Packard, IBM, Rockwell, Westinghouse, 3M, and Honeywell.

### 2.3.3 JIT with Kanbans

JIT systems try to eliminate all waste within an organization. The aim is to meet production targets using the minimum amount of materials, with the minimum amount of equipment, the smallest number of operators, and so on, and by making sure all operations are done at just the time they are needed. One approach to achieving JIT operations is to use kanbans. Kanban is a tool used in a JIT production system to implement 'pull' type production.

The JIT approach to control manufacturing systems with "kanbans" has received much attention since early 80's, see for examples Chase and Aquilano [ChasAq 85], Huang *et. al* [HuanReTa 83], Suzaki [Suza 87], Krajewski *et. al.* [KrKiRiWa 87], and Shingo [Shin 88]. The idea of kanban originated from US supermarkets [Ohno 88], where customers get: (1) what is needed, (2) at the time it is needed, and (3) the amount needed. In the kanban systems, cards that contain information such as the job type, the quantity of parts to carry, and the kanban type, have become crucial in production management. With the movement

of the cards, information becomes tangible and easily understood. A detailed overview of kanban systems is given by many authors, including Huang *et. al.* [HuanKu 96].

The kanban system is a 'pull' system in the sense that the production of the current stage depends on the demand of the subsequent stages, that is, the preceding stage must produce only the exact quantity withdrawn by the subsequent manufacturing stage. At each stage, the information about the product name, code, volume, and so on, can be easily obtained from the kanbans. In this way, the kanban system was created to indicate what is needed at each production stage, and to allow various stages to efficiently communicate with each other. The company's production plan is given only to the final assembly line: a message is passed backwards to the preceding stage to start production. When parts or materials are withdrawn from the preceding stage, a chain of communication is established with each of the relevant preceding stages, and every stage automatically knows how much and when to produce the parts required.

The kanban is used for two functions: to place a production order and to authorize withdrawal of WIPs (work-in-process). More precisely, a kanban is a job card that is attached to a storage and transport container, and it accompanies a part through the assembly process. It identifies the part number and container capacity, along with other information. There are two main types of kanban : (1) Production Kanban (P-Kanban): signals the need to produce more parts, and (2) Conveyance Kanban (C-Kanban): signals the need to deliver more parts to the next work centre, also called a "move kanban", or a "withdrawal kanban". When a station needs more parts, C-kanban is put on an empty container. This gives permission to take the container to the area where stocks of work in progress is kept. A full container is then found, which has a P-Kanban attached. The P-kanban is removed and put on a post. This gives a signal for the preceding station to make enough to replace the container of parts. A C-kanban is put on the full container, giving permission to take it back to the station. However, this system has a stock of work in progress, albeit it small. The kanban system makes sure that stocks of work in progress can not accumulate.

The weakness of a 'pull' system (kanban) is that following the JIT production approach is essential, especially concerning the elements of short setup times and small lot sizes. The

'pull' system is often difficult to implement when lead times are long, for example suppliers are located far away from a factory, that it is impractical to react to demand information.

Similarly to what has been mentioned earlier in section 2.3.2, JIT with kanban cannot be implemented without full worker understanding and co-operation. Management must ensure that workers understand their new roles and accept this approach. Just as employees are required to change, so are the company's suppliers. Under this approach, suppliers are treated much as internal work centres are treated. Suppliers receive kanban cards and special containers, and they are expected to make frequent deliveries just in time for the next production stage. Suppliers are viewed as the external factory and as a part of the production team.

Kanban is the method of production authorization and materials movement in the JIT system. Notably, kanban is a subsystem of JIT, used to control the sequencing of jobs through a sequential process. In its largest sense, JIT is not the same thing as a kanban system, and a kanban system is not required to implement JIT, although JIT is required to implement a kanban system and the two concepts are frequently equated with one another.

### 2.3.4 Lean supply / enterprise

A recent theory closely linked to the theory of supply chain management is that of lean enterprise. Womack, Jones and Roos produced the seminal work in this area when they published, *The Machine that Changed the World* in 1990 [WomaJoRo 90]. From their five-year worldwide study of the motor industry in the 1980s, they assert that the lean production system, which later lead to the concept of the lean enterprise, is the superior way of producing manufactured goods. In making their assertion they draw mainly on the evidence of Japanese automobile companies which, they argue, have developed the means for designing and building cars in less time with fewer people and lower inventories than Western manufacturers.

Their concept of lean production focused on: (1) eliminating unnecessary steps, (2) aligning all steps of an activity in a continuous flow, (3) recombining labour into cross-functional teams dedicated to that activity, and (4) continually striving for improvement. According to Womack, Jones and Roos [WomaJoRo 90] this could result in developing, producing, and distributing products in half or less time and expense, increased flexibility and customer

responsiveness. The term 'lean' was used to describe Japanese systems, since in comparison with mass production methods, they use less of everything to achieve a better product, which closely matches customers' needs. Central to their idea is the notion of *muda*, or waste, which must be identified and eliminated. This was an important piece of work, particularly because they promoted the idea of managing a network of both suppliers, suppliers' suppliers, customers, customers' customers and so on.

Later Womack and Jones developed these ideas to encompass up and down the value chain to form a continuous value stream, leading to the so-called lean enterprise: a group of individuals, functions, and legally separate but operationally synchronized companies, see [WomaJo 94] and [WomaJo 96]. The goal is to analyse and focus on a value stream so that everything involved in supplying goods or services is done in a way that provides maximum value to the customer.

A successful implementation of a lean production approach in manufacturing results in shorter manufacturing and new product lead times, team-based work organization with responsibility for quality and a smaller component supplier base providing deliveries. A key feature is that fewer resource inputs are required by the manufacturing system, that is less factory space, less tooling investment, fewer parts, shorter production operations, less unproductive time needed for set-ups, development of new products in half the time using half the engineering hours, and etc. At the same time there is pressure for higher output performance to be achieved, that is better quality, higher technical specifications, and greater product variety.

The lean production approach to control manufacturing systems has received much attention and discussion on numerous issues relating to it is given by many researchers including Burcher *et. al.* [BuchDuRe 96], Lee *et. al.* [LeeOa 96], Kitayama *et. al.* [KitaBe 96], and Lamming [Lamm 93].

Despite the apparent superiority of lean production compared with conventional mass production systems, however, there are now some questions being asked in Japan concerning its robustness as an approach to coping with future economic and market conditions [KitaBe 96]. The first is that Womack and his colleagues conducted their research at the time of Japan's "bubble economy" of late 1980s during conditions of a bull

stock market and low interest rates. Domestic demand for consumer products was at an all-time high level and the output from Japan's factories could also remain high. The main competitive objective of companies, therefore, was to increase market share by reducing costs, and thereby prices, as well as offering a greater variety of products with more features. The second point is that Japan has a vehicle inspection system that encourages owners to scrap their cars and buy new ones. There is little demand for second-hand vehicles. Also, the average model age of Japanese cars is less than two years compared with around four to five for a typical European or American product. Therefore, this has enabled automobile manufacturers to rely on a large domestic market which has been willing to accept the latest models readily, thereby increasing the rate of new product development.

Apart from the work by Womacks and his colleagues, in 1993 Lamming asserted the concept, or paradigm, as a more realistic and appropriate method of collaboration than partnerships which are often 'false' because of one dominator, that is the customer. Lamming's contributions to this theory, initially by the book *Beyond Partnership: Strategies for Innovation and Lean Supply* [Lamm 93], are significant in that he provides a focus on 'lean' at the level of what used to be the chain. A divergence in view within the concepts of 'lean' exists between Lamming's concept of lean supply ([Lamm 93], [Lamm 96]) versus the lean enterprise approach by Womack and Jones ([WomaJo 94], [WomaJo 96]). According to Lamming, the underpinning principle of supply chain management is the notion that the customer must be satisfied. With that notion, all supply chain activities are undertaken with that perspective in mind, which is why activities such as supplier development are promoted, and the customer is the one showing the supplier how to run their businesses. Lamming argues that the concept of 'lean', however, does not approve of this idea of blaming and correcting the suppliers. Lamming focuses on developing 'lean' in the dyadic relationship and then cascading the improvements upstream. Womack and Jones on the other hand seem to be more concerned with optimizing the whole 'value stream'. It should be noted, however, recent work within supply chain management and logistics stresses that it is the end customer and not the intermediate customer who should be satisfied. The gap between the theories, supply chain management and lean supply in particular, in that respect seems to be minimal, and mostly centred around the objective of operations management: cost minimization/value creation versus a broader range of performance

objectives. For more surveys on the recent development of this idea, the reader can refer to [Anon 00] and the references cited therein.

Today, many organizations have adopted the lean thinking paradigm [WomaJo 94] in their drive to optimise performance and improve competitive position. The principles and demonstrated benefits of lean production are so well known and compelling that there are now very few countries and industries where its influence, along with its associated methodologies such as just-in-time (JIT), total quality management (TQM), and total productive maintenance (TPM), have not been felt, see for example De Meyer *et. al.* [DeMeWi 92], Flynn *et. al.* [FlynnSS 95] and McKone *et. al.* [McKonSC 01].

## 2.4 Approaches to analysis and design of supply chain systems

Supply chain analysis and design requires both static and dynamic information from different parts of a company. The static data include plant production rates, plant locations, warehouses, and customers as well as warehousing and transportation costs. The dynamic data includes forecasts, orders, and current deliveries. The ability to analyse and understand effectively the many aspects of the supply chain system is important for effective decision-making. The suitability of the analysis tool to use depends on the requirement and the level of detail the solution requires.

This section examines the various ways in which supply chain systems have been modelled and analysed. Generally, there are four distinct methodologies in which the supply chains have been modelled, namely:

(1) the continuous time differential equations models,
(2) the discrete time difference equations models,
(3) the classical operational research techniques, and
(4) the discrete event systems simulation models.

### 2.4.1 Continuous time differential equations models

The approach using the differential equations started in the late 1950s and, for example, Forester [Forester 61] used a simple first order differential equation system for a supply

chain. Also, examples on the use of continuous time differential equation models are given in Porter and Taylor, [PortTa 72]. However, his model is only for a production/inventory system, and not for a general supply chain system.

The model is based on the following set of equations:

$$d\,i(t)/dt = p_a(t) - d(t)$$

$$d\,p_a(t)/dt = \alpha(p_d(t) - p_a(t))$$

where $p_d(t)$ is the desired production rate, $p_a(t)$ is the actual production rate, $d(t)$ is the demand and $i(t)$ is the inventory level.

Bensoussan *et. al.* [BensHuNa 74] in their book applied the optimal control theory for these type of systems, where the cost structure is accounted in the production strategy. Later, Towill [Towill 92], Wikner *et. al.* [WiknToNa 91], Towill and De Vecchio [TowiDe 94], and Evans *et. al.* [EvanToNa 95] continued the work of Forester using two and three echelons. Most of these papers use the models for simulation purposes only. No sensitivity analysis has been carried out on these models and also, no cost base analysis is covered by these models as they are more concerned with the dynamics.

### 2.4.2 Discrete time difference equations models

Discrete time difference equations have also been used. By discretizing the continuous time systems found in [PortTa 72], Porter and Bradshaw [PortBrad 74] used simple state feedback design to generate piecewise constant controllers in production-inventory systems. Bradshaw and Daintith [BradDain 76] used similar techniques on larger cascaded systems that are more recognisable as supply chains. Constraints on the magnitude of the control signal, which can be interpreted as capacity constraints, are included in [BradErol 80]. In his book, Elmaghraby [Elm 66] analyses simple discrete systems with stochastic demand using Z-transform methods. Discrete exponential smoothing is used in Burns and Sivazlian [BurnSiva 78], along with signal flow graphs, to represent the system. Elementary Z-transform techniques are then used to investigate demand amplification.

Models described by these equations have the advantages, in the sense that the dynamics involved are clearly revealed, and there exists a mature body of applicable theoretical research to analyse this type of models. Similarly, there are many limitations with the application of these models. These might be the limitation to deal with batch and sequencing problems, and the difficulty of incorporating transportation costs in the model.

As an example, Tzafestas and Kapsiotis [TzafKa 94] used the following discrete time equations to describe chains of suppliers:

$$x_1(k+1) = x_1(k) + u_1(k-\theta_1) - d(k)$$
$$x_2(k+1) = x_2(k) + u_2(k-\theta_2) - u_1(k)$$
$$x_3(k+1) = x_3(k) + u_3(k-\theta_3) - u_2(k)$$
$$\vdots$$
$$x_i(k+1) = x_i(k) + u_i(k-\theta_i) - u_{i-1}(k)$$

where $d(k)$ is the demand at time $k$, $x_i(k+1)$ is the inventory level at echelon $i$ at time $k$ and $u_i(k-\theta_i)$ is the order plan of the $i^{th}$ level, delayed by an amount (time interval) $\theta_i$.

### 2.4.3 Classical operational research techniques

Operational Research (OR) techniques are also used to model the supply chain. OR theory comprises a disparate collection of mathematical techniques, such as linear programming, integer programming, queuing theory, Markov chain and dynamic programming. Altiok [Altiok 95] described how to use Markov chains to approximate the steady state of a production-inventory systems.

The OR techniques are recognized as being useful in solving local tactical problems, but the impact of these solutions on the global behaviour of the whole supply chain can only be assessed using dynamic simulation. Hax and Candea [HaxCa 84] suggested the following two-stage approach which takes advantage of the strength of both simulation and OR optimisation based techniques: (1) use an OR optimisation model to generate a number of least-cost solutions at the macro level, taking into account the most important cost

components, and (2) to use simulation model to evaluate the solutions generated in the first stage.

### 2.4.4 Discrete-event systems (DES) simulation models

Discrete-event systems (DES) simulation models are also a very popular approach for these types of problems. These models present many advantages over the other methods listed above. Consider, as an example, the differential equations governing the behaviour of a series of queues at a supermarket. The modelling of phenomena such as queue swapping (when customers jump to shorter queue) and variable service speed (faster when there are more customers) would make these equations incomprehensible.

The application of any other methodologies as reviewed in the previous sections (2.4.1, 2.4.2, and 2.4.3) would then be virtually impossible. However, such rules can easily be incorporated into a DES simulation model. The DES approach allows different combinations of decision strategies to be evaluated and thus provide adaptivity necessary for efficient use in dynamic, on-line environments. Compared with the previous DES tools for example GPSS, and SIMAN etc., the many sophisticated DES simulation packages available today, able to provide a more detailed simulation capability, even for real-time planning, scheduling and control, examples are ARENA, Witness, etc. For example, Tipi and Bennett presented an on-line analysis and control of a virtual enterprise using Arena software, [TipiBe 99].

Detailed reviews of the modelling methods described above are given in Riddalls *et. al.* [RiddBeTi 99b], Beamon [Beamon 98] and Beamon and Ware [BeamWa 98].

### 2.4.5 Agent-based modelling approach

In addition to the above methodologies, there is an emerging concept originating from the field of computer science that has been adopted to the problem of modelling and analysing supply chains, namely the agent-based modelling approach.

The concept of agent-based modelling approach has been explained by many authors, including Parunak *et. al.* [ParuSaRi 98]. Parunak *et. al* [ParuSaRi 98] describe an agent-

based modelling as consisting of a set of agents that encapsulate the behaviours of the various individuals that make up the system, and execution consisting of emulating these behaviours. They identify the feature of a model constructed and experimented with the agent-based modelling approach as able to maintain a given set of conditions as long as desired, permitting the collection of statistically relevant time series. This approach allows the exploration of the dynamic nature of the model that can lead to important insights of great practical significance.

Swaminathan *et al.* [SwaSmSa 98] used the concepts of agents to develop a modular and reusable framework with primitives that allow development of realistic supply chain models. The models are composed from software components that represent types of supply chain agents, examples, retailers, manufacturers, transportations, and their constituent control elements, examples, inventory policy, and also their interaction protocol examples, message types. However, they do not provide with any empirical demonstration to validate their proposed theoretical framework.

A conceptual and prototypical models of an adaptive production control system based on agent technology is presented in Ottaway and Burns [OttaBurn 00]. In the system presented both work-pieces and resources are represented by agents. Supervisory agents that serve to balance the production load across resources and maximise overall throughput, are introduced as the production load on the resources increases and removed as the load across decreases. Simulation studies based on a deterministic model show improvements in throughput, resource utilisation, and work-in-process (WIP) inventories.

Fox *et.al* [FoxBarTe 00] investigated the construction of an agent-oriented software architecture for managing the supply chain at the tactical and operational levels that views the supply chain as composed of a set of intelligent (software) agents, each responsible for one or more activities in the supply chain and each interacting with other agents in planning and executing their responsibilities. They present a building shell which provides generic, reusable, and guaranteed components for some of the required elements of the architecture. They claim that their approach is promising in terms of naturalness of the co-ordination model, effectiveness of the representation and power, and the usability of the programming tools.

Parunak *et. al.*, [PaSaRiCl 99], reported a simulation work utilising the agent-based modelling approach of a linear supply chain with four company agents consisting of a consumer demand for the finished product, a company comprising of two intermediate firms that is, a centralised shipping facility and a manufacturing facility, and a supplier raw materials. Only one product is modelled, and it is manufactured from only one raw material. The two intermediate company agents each have production planning and inventory control algorithm agents to determine what inputs to order from their suppliers, based on the orders they have received from their customers. The model produced some interesting behaviours in terms of the variability in orders and inventories at the various company agents. However, the simulation model is run in a fixed time steps whilst at each time step, it is set to execute a predetermined order of actions.

## 2.5 Related research work on modelling supply chains

One of the pioneering works dealing with the stochastic nature of the integrated supply chain is credited to Midler [Mid 69], who developed a dynamic model based on optimal control theory for selecting an optimal combination of transportation modes, commodity flows, and re-routing of carriers from customers to suppliers over a multi-period planning horizon.

Tapiero and Soliman [TaS 72] utilised optimal control theory to solve multi-commodity transportation, multi-regional production and inventory planning problems over time with uncertain demand. Despite its merit, the model combining linear and parametric programs created severe computational difficulty.

One of the earliest efforts to create an integrated supply chain model dates back to Glover *et. al.,* [GloJKKM 79]. They developed a computer-based production, distribution, and inventory planning system that integrated three supply chain segments comprised of supply, storage/location, and customer demand planning. The core of the system was a network model and diagram that increased the decision maker's insight into supply chain connectivity. The model, however, was confined to a single-period and single-objective problem.

Cohen and Lee [CoL 89] developed a mixed-integer, non-linear, value-added chain model that coordinated the supply chain process comprised of sourcing, centralised production planning, and inter-plant transhipment. The model incorporated capacity, demand, and production constraints.

Lee and Billington [LeeB 93] attempted to integrate the material flows of marketing, manufacturing, and distribution processes by developing a stochastic program. Their model was designed to determine the material ordering policy, the customer service level for each product, and postponement strategies. Similarly, Lee and Feitzinger [LeF 95] and Swaminathan and Tayur [SwT 99] presented stochastic models to formulate postponement (delayed product differentiation) strategies.

Arntzen *et. al.,* [ArnBHT 95] presented a mixed-integer programming model, called global supply chain model (GSCM) which evaluated global supply chain alternatives involving multiple products and multiple stages (echelons). More specifically, GSCM took into account the interdependence of production, inventory, material handling and transportation.

Mak and Wong [MakWong 95] considered the problem of designing an optimal integrated production-inventory-distribution system, aiming to minimise the overall costs, including inventory holding costs, delivery costs, manufacturing costs and shortage costs. An evolutionary algorithm was employed for the solution of the problem. An integer programming formulation of the problem was adopted, and the solution was represented using variables of the model.

Ashayeri and Rongen [AsR 97] refined a grid model and the multi-criteria solution method called ELECTRE to formulate the distribution centre repositioning strategy based upon the analyses of material flows, distribution centre locations, and throughput times. Although the proposed model and solution method were simple to use, they were confined to single-period and un-capacitated problems.

Disney *et al.* [DisNaTo 97] addressed the problem of controlling a production and inventory system. Transfer functions were used for the modelling of the problem, illustrated in the form of block diagrams. The solution of the problem was represented by the variables of the

transfer functions, and a fitness measure was designed based on stock reduction, production robustness and inventory recovery.

Min and Melachrinoudis [MiM 99] configured a multi-echelon supply chain networks connecting material flows among suppliers, manufacturers, break-bulk terminals, and customers. Their analytic hierarchy process-based model also considers contingency planning associated with supply chain reconfiguration. It, however, did not consider capacity constraint and risk factors. More recently, Melachrinoudis and Min [MeM 00] extended their previous work by designing a multi-objective, multi-period integer programming model that determined the optimal relocation site and phase-out schedule of a combined manufacturing and distribution facility from supply chain perspectives.

Riddalls *et. al.* [RiddSB 01] applied an optimal control algorithm incorporating a cost structure implied by quantity discounts to a differential equation model of an inventory system. Rather than using a demand forecast, this approach is intended to regulate the system in real time in response to inventory variations. Some examples illustrate how the system response is generated and how it is affected by quantity discounts. The contribution of quantity discounts to the well-known demand amplification effect is also demonstrated.

In an effort to integrate inventory, transportation and location functions of a supply chain, Nozick and Turnquist [NoT 01] proposed an approximate inventory cost function and then embedded it into a fixed-charged facility location model. The fixed-charge facility location model was designed to consider a trade-off between demand coverage and cost associated with the location of automobile distribution centres. Although the model deals with multiple objective (service-cost trade-off) issues, it is confined to a single period, single echelon problem with no capacity constraint.

All the above literatures showed that mathematical programming techniques (e.g. mixed integer programming) and mathematical model-based optimisation theory and evolutionary computing methods have dealt successfully with many supply chain problems, including the production-inventory scheduling problems, especially those of a static and deterministic in nature. However, a large number of practical problems cannot be solved by these '*analytical modelling*' methods only, especially in situations where the systems are large, complex, dynamic, and stochastic. Simulation provides an alternative method for detailed

analysis of the complex real world systems such as the supply chain. When the *'analytic modelling'* has limitations on the range of features that can be modelled, a simulation model can be constructed to any level of detail.

Several examples will now be given to indicate how simulation has been used in the area of supply chain related problems. Given that a simulation model is well-suited for evaluating dynamic decision rules under 'what-if ' scenarios, a few attempts have been made to develop simulation models to improve supply chain performances. There are quite a number of reports on the modelling of supply chains dynamics adopted to simulation approach. These include Towill *et. al.,* [TNW 92], Badri [Badri 99], Bhaskaran [Bhaskar 98], Sadeh *et.al* [SaHiKjTs 99], and Tipi and Bennett [TipiBenn 99].

More specifically, Towill *et. al.* [TNW 92] used influence diagrams to visualise the cause-and-effect relationship between the decision rule and the improvement of supply chain performances. The main purpose of the study is to create a best decision rule that will allow the decision maker to reduce lead times, compress the distribution channel and co-ordinate information flow throughout the supply chain.

Bhaskaran [Bhaskar 98] conducted a simulation analysis of supply chain instability. He shows how supply chains can be analysed for continuous improvement using simulation. The focus is on a stamping pipeline in an automobile supply chain based on operating data from General Motors.

Badri [Badri 99] developed a simulation-based decision-support system for multi-product inventory control management to enhance the competitive advantage of a furniture manufacturing firm using the simulation language SLAMSYSTEM and some statistical models. He claimed that the model allows managers to examine different inventory systems and policies without resorting to unrealistic assumptions and methods or having to use complicated mathematical techniques.

Sadeh *et.al.,* [SaHiKjTs 99] proposed an architecture that aims at providing a framework for coordinated development and manipulation of planning and scheduling solutions at multiple levels of abstraction across the supply chain. The architecture is configured around a blackboard architecture to allows for the easy integration of multiple planning and

scheduling modules along with analysis and coordination modules. They claimed that the architecture has been validated through experimentation of supply chain configurations.

Tipi and Bennett [TipiBenn 99] conducted a comprehensive investigation on the use of dispatching rules to provide on-line scheduling for a production system in a dynamic and stochastic environment. A model of a manufacturing system, referred to as a virtual enterprise, comprising of three manufacturers each with a different number of machines was developed. Manufacturer 1 has six processing resources or machines, while each of the manufacturers 2 and 3 have two machines. The job arrivals or orders, is assigned to have a fixed value and thus is considered to be deterministic. The investigation is carried out using discrete-event systems for simulation software, ARENA.

Using a DES as the simulation tool, Tipi 2000 [Tipi 00] takes total cost as the performance measure to analyse the performance of a packaging industry supply chain. Several tests were performed to understand the relationships that would occur in the supply chain system. The operations have been defined by an individual cost function such as holding cost, production cost, and penalty cost. The work relies on the use of total cost as the primary measure, but does not consider the occurrences of uncertainties (disturbances).

## 2.6 Modelling issues

The main drawback of most analytical or mathematical models is the fact that numerous constraints have to be satisfied before results can be applied in practice. Also, the analytical models present the simplified form of the problem, and the main issue which might influence the behaviour of the chain might be ignored. Most models only take few variables into consideration, for example, inventory and cost of holding finished goods, and ignore other costs such as order processing, transportation and penalty cost. Furthermore these models are not correlated in time and ignore the complex relationships that occur if upstream echelons fail to serve downstream echelons. In addition to requiring too many simplifications to model realistic problems, the mathematical optimisation techniques have limitations in that they deal with static models, typically by considering annual, or average demand and do not take into account of changes over time. However, mathematical techniques have been successfully applied to the static data to determine potential solutions to problems. For example, these techniques may generate the best set of

locations for new warehouses, an efficient route for a truck to take, or an effective inventory policy for a retail store.

On the other hand, DES simulation tools take into account the dynamics of the system and are capable of characterizing system performance for a given design, thus allow the logistic systems to be modelled more realistically. In [AminAl 97], Amin and Altiok used the discrete-event language SIMAN to model a multi-product, multi-stage manufacturing system. This can be thought of a supply chain in microcosm. However, DES tool has been originally designed for modelling of manufacturing systems. Considering the different scenario and the complexity of a supply chain system, to implement a model using a discrete event language may be appropriate, however, the modelling concept to use also granted a thorough consideration.

## 2.7 Control strategies

A representative survey of the current control strategies on designing supply chain network and the co-ordination control of supply chain planning processes is provided in this section. A discussion on centralised versus decentralised control have been extensively discussed in [SimKS 00].

### 2.7.1 Optimisation

Within any supply chain are many systems, including various manufacturing operations, storage, transportation, and retail systems. Managing any one of these systems involves a series of complex trade-offs. For example, to efficiently run a manufacturing operation, set-up and operating costs must be balanced with the costs of inventory and raw materials. Similarly, inventory level is a delicate balance between holding costs, order set-up costs, and required service level. Also, there is a balance between inventory costs and transportation costs, because transportation typically involves quantity discounts of one type or another. However, all of these systems are connected, that is, the outputs from one system within the supply chain are the inputs to the next system. For example, the outputs from the manufacturing operation may be the inputs to a transportation or storage system, or both. This will be true whether or not there is a common owner for several of the systems

in the supply chain. If there is an effort to reduce the overall system cost, this could lead to an increase in costs in one of the system. Thus, an attempt to find the best set of trade-offs for any one stage is not sufficient.

Various quantitative models pursue the highest overall efficiency of whole supply chain have been reported. For example, Cohen and Lee [CoL 88] used mixed-integer programming to develop a planning model to optimise material supply, production and distribution processes. As quoted earlier in section 2.5 of Chapter 2, Arntzen *et. al* [ArnBHT 95] used a methodology similar to Cohen and Lee's research to develop a planning model for resource allocations in a global production and distribution network. However, in practice, every supply chain partner plans its operations separately in terms of their interests and conflicts between customer requirements and local decisions always exist.

The methods to explore supply chain inter-relationships, detect process key problems and co-ordinate planning processes in different supply chain partner has been reported in [LiOB 99] and [LiMcdPB 01]. However, the efforts on developing tools for decision support of co-ordinated planning in supply chains are still lacking.

Li and O'Brien [LiOB 99] developed a decision-support model which hierarchically optimises supply chain processes-each process is optimised respectively and then the best combination of supply chain partners with desired manufacturing strategies are determined by minimising overall gaps between customer requirements and operational performance of each supply chain processes. In the research, the way to deal with conflicts between processes was still not discussed. An interactive decision-support system on the Web for efficient supply chain planning co-ordination is described in [ LiMcdPB 01]. In the paper, Li *et. al.* extended the groundwork of Li and O'Brien [LiOB 99] to develop a Web-based system that combines Quality function deployment (QFD) approach created in Japan in the 1970s as a product evaluation tool, with Internet technique to co-ordinate optimised planning processes through Internet. The QFD approach is employed as co-ordinators to assist solving conflicts in supply chain planning processes by capturing customer requirements and transforms these requirements into technical terms for follow-up actions at every stage of product design and manufacturing processes.

The concept of optimising a supply chain system can thus be asserted as follows. If the system is not co-ordinated, that is, each facility in the supply chain does what is best for that facility, the result is *local optimisation*. Each component of the supply chain optimises its own operation without due respect to the impact of its policy on other components in the supply chain. The alternative to this approach is *global optimisation*, which implies that one identifies what is best for the entire system.

### 2.7.2 Centralised control

In a centralised system, decisions are made at a central location for the entire supply chain. Typically, the objective is to minimise the total cost of the system subject to satisfying some service-level requirements. This is clearly the case when the network is owned by a single entity, but it is also true in a centralised system that includes many different organisations. In this case, the savings, or profits, need to be allocated across the network using some contractual mechanism. Centralised control requires global optimisation in order to achieve the aim of best performance and efficiency.

A centralised network will be at least as effective as a decentralised one because the centralised decision makers would make, but also have the option of considering the interplay of decisions made at different locations in the supply network. In a logistic system in which each facility can access only its own information, a centralised strategy is not possible. With advances in information technologies, however, all facilities in a centralised system can have access to the same data. In this case, information can be accessed from anywhere in the supply chain and is the same no matter what mode of inquiry is used or who is seeking the information. Thus, centralised systems allow the sharing of information and, more importantly, the utilisation of this information in a way that reduce the *bullwhip effect* , or demand amplification and improve forecasting. Finally, they allow the use of co-ordinated strategies across the entire supply chain: strategies that reduce system-wide costs and improve service levels.

### 2.7.3 Distributed / decentralised Control

A supply chain is an inherently decentralised organisation comprised of various retailers, manufacturers, and distributors with different owners and different objectives, distributed

spatially and temporally. Such a series of facilities forms a supply chain system in which the tasks and intelligence necessary for task execution is physically distributed throughout the chain. In a distributed, or decentralised system, each facility identifies its most effective strategy without considering the impact on the other facilities in the supply chain. Thus, a distributed system leads to local optimisation. In the context of designing the control strategy, a distributed system reduces the complexity of the system by localising the information and control. Maintainability and modifiability will be improved because of modularity and self-configurability. In addition, software development costs will be reduced by eliminating the need for supervisory level modules.

In a distributed system it is often helpful to form partnership to approach the advantages of a centralised system. The variations in demand to suppliers from retailers in traditional retailer-supplier relationship are far greater than the variation in demand seen by retailers. In fact the suppliers have better knowledge of their lead times and production capabilities than retailers do. Thus, as margins get tighter and customer satisfaction become even more important, therefore it make sense to create cooperative efforts between suppliers and retailers in order to leverage the knowledge of both parties. For example, Wal-Mart and Proctor & Gamble, whose partnership begun in 1985, has dramatically improved P&G's on-time deliveries to Wal-Mart while increasing inventory turnovers, [BuzzOr 95].

## 2.8 Summary

Most of the related work in this area shows indication of at least one or several of the following shortcomings.

- Most of the research works in this field have put considerable effort to optimise the performance of a horizontal slice of a supply chain, such as coordination among parts that share a common resource. The need to improve the performance of the vertical slice, that is, the supply chain connecting raw material to finished product, by controlling the transmission of schedule instability and the resulting inventory fluctuation is often overlooked.

- Most of the research works have been using the approach of decomposing a problem into smaller, more manageable pieces, with the assumption that the collection of

solutions to these smaller problems would then be combined to yield a solution to the larger problem. Nevertheless, to model and analyse a dynamic system as comprising of many static problems will not produce desirable results. In this research, the retailer, distributor, manufacturer, and raw material supplier are to be modelled as a network of integrated organisations, each performing its supply chain function.

- Most approaches produce results that are difficult to be implemented in real world. One inherent attribute about DES modelling (and to mention also, the agent-based modelling) is the ease with which to translate back the models behaviour into practice. Since the model is expressed and modified directly in terms of behaviours, implementation of its recommendation is simply a matter of transcribing the modified behaviours of the system's model behaviour into task descriptions for the underlying physical entities in the real world.

Notably, there is substantial literature on production-inventory control problems adopted to OR methods as well as to mathematical-based model using differential equations, or to evolutionary computing to achieve optimal solution, and quite a well developed literature on approaching the supply chain problems through simulation and modelling. However, few explore the issues on the supply chain production-inventory control adopted to simulation using the concept of modelling the entire system in one model. Considering the defining benefits of modelling and simulation with a DES tool, the motivation to embark on this work is based on the potential for extending and scaling the research in supply chain production-inventory control using the methodology to be presented in Chapter 3.

# Chapter 3

# Discrete-Event Simulation (DES) Modelling of Supply Chain System

## 3.1 Introduction

Large and complicated systems such as a supply chain in which stochastic and dynamic variables appear and multi-level production-inventory systems exist, are most conveniently investigated by simulation. Using a packaging industry supply chain as an example, this chapter aims to give a coverage of the modelling, and simulation of a supply chain with a discrete-event simulation (DES) tool. A base model, the result of this work, will be expanded for further investigations to answer related questions on supply chain.

The analysis and design of a supply chain requires various information from different parts of the system. The supply chain variables include: (1) *dynamic data*; forecasts, orders, production sizes (delivery sizes), and inventory levels, (2) static data; production capacity, plants location, and warehousing, and (3) *disturbance*; late delivery, failing of production facilities, and customer cancel orders. Existing analytical methods could not handle all the dynamically changing internal supply chain variables. Simulation using a DES tool is an effective tool for the dynamically changing supply chain variables, see Riddalls *et.al.* [RiddBT 99a], and Ingalls [Ingalls 98].

DES simulation tools, for example ARENA, were originally designed for use in simulating manufacturing systems, and are effective in evaluating resource flows (such as machinery, people, and materials). In modelling a supply chain, two main features have to be modelled: the resource flows, and the modelling of the arrival of orders or messages which shall be regarded as a feedback process. However, the

modelling of orders has rarely been addressed due to the fact that a DES tool is intended for use in attacking a direct process oriented problem similar to the manufacturing system. This chapter aims to address the task of formulating such an approach.

This chapter describes a modelling approach undertaken to produce a computer simulation model of a supply chain system using a DES language. First, an introduction to the DES is presented. Next, an explanation on the design of a conceptual model of the supply chain system is deliberately discussed. The conceptual model is formulated to be independent of any programming or simulation language. Then, the design and development of an implementation model based on the conceptual model associated to ARENA simulation language is presented.

## 3.2 Introduction to discrete-event simulation (DES)

*Discrete-event simulation* is the term used to describe a simulation of a system whose constituent elements can be modelled as interacting with one another only at discrete points in time. Programming languages for DES therefore contain statements to perform time forwarding operations such as "*Start machine M in 15 minutes*" or "*Wait here until N seconds have elapsed*," where *N* is a random variable drawn from some particular statistical distribution. Statements like this distinguish discrete-event simulation languages from continuous simulation languages that model systems governed not by discrete logic (such as whether something is in a queue or not, or whether one variable bears a particular relationship to another) but by systems of simultaneous equations.

The essential elements of DES programming languages are language features for defining systems and the objects that exist in them, and for manipulating the behaviour of objects over time so as to mimic the behaviour of a real or hypothesised system. DES models are used to study the time-dependent behaviour of systems (DES is event driven), starting from an initial state (specified by a population of objects with particular attributes and relationship values) and driven by defined processes governed by both internal logic, external inputs, and the passage of simulated time. Several models have been built using DES to simulate the behaviour

of production and business, military operations, and computer and telecommunication networking. See for example [HillMMc 02], [Al-Aomar 00], and [Obaidat 02]. Mainly, these models are used to study policies, explore alternatives, and estimate measures of system performance. Discrete-event simulation has a commendably long and successful track in the improvement of manufacturing processes, see Law and McComas [LawMc97].

### 3.2.1 Modelling schemes in DES

There are two modelling schemes in discrete-event simulation: the event scheduling scheme and the process-oriented simulation scheme. In the first scheme, the modelling and computation work is centred around the events. This allows the programmer to control everything, have complete flexibility with regards to attributes, variables, and logic flow, and to know the state of everything at any time. This could be coded up in most languages, for example FORTRAN, or C++. In the second scheme, the simulation view centres on the processes that entities undergo. This scheme allows big models to be built without the extreme complexity they would require as in the first scheme. It does, though require more behind the scene support for chores like time advance, keeping track of time-persistent statistics, and output-report generation. Discrete-event simulation languages like SIMAN, ARENA, SIMSCRIPT have both process-oriented and event scheduling schemes capabilities.

Detailed information about the principles in discrete-event simulation, and the description of these schemes can be found in [Banks 98] and [CaLa 99], respectively. A brief description for each scheme is given below.

#### 3.2.1.1 The event scheduling scheme

The event scheduling scheme describes a way to construct sample paths of discrete-event simulation for the purpose of simulation. A sample path is a timing diagram with events denoted by arrows at the times they occur, and states shown in between events. The event scheduled scheme should be thought of as a procedure for generating sample paths and driven by a given clock structure. A scheduled event list contains all feasible events at the current state sorted on the smallest-scheduled-time-first. A clock structure is a set of sequences, one for each event, defining event

lifetimes, and acting as input to the model. This can be thought as having a master controller keeping track of all events, entities, attributes, variables, and statistical accumulators.

The description on the operation of this scheme can be found in many literatures. Cassandras and La Fortune [CaLa 99] described it as follows: All feasible events at any state are placed in a scheduled event list along with their occurrence times in increasing order. The next event is the one with the smallest occurrence time. When an event is activated, its clock is assigned a lifetime from the associated clock sequence. An event is deactivated when a different event occurs causing a transition to a new state. When a new lifetime is needed for some event, it is obtained from a random variate generator, which contains all information regarding the event lifetime distributions. From a computer implementation standpoint this scheme constitutes the cornerstone of discrete-event computer simulation.

#### 3.2.1.2 The process-oriented simulation scheme

An alternative way to simulate DES is the process-oriented scheduling scheme. The process-oriented simulation scheme is suitable for resource-contention environments, where it is convenient to think of "entities", for example customers undergoing a process as they flow through the DES. The behaviour of the system is described through several such processes, one for each type of entity of interest. In the process-oriented scheme, a process is viewed as a sequence of functions triggered by an entity. There are logic functions, where the entity triggers instantaneous actions, and time delay functions, causing the entity to be held for some period of time, either specified or dependent on the state of the system. Most commercially available discrete-event simulation software packages follow the process-oriented scheme. Examples include GPSS, SIMAN, SIMSCRIPT, and EXTEND.

These terms are described here, because they are going to be used in explaining the way the actual model has been built using DES software. In summary, the main components of a process-oriented simulation scheme are the following:

**System**: A collection of entities (example, machines or jobs) that interact together over time to accomplish one or more goals.

**Model**: An abstract representation of a system, usually containing structural, logical or mathematical relationships, which describe a system in terms of state, entities and their attributes, sets processes, events, activities and delays.

**System state**: A collection of variables that contain all the information necessary to describe the system at any time.

**Entities**: Objects requesting service (example, parts in a manufacturing system, jobs in a computer system, packets in a communication network, vehicles in a transportation system). Each entity type is characterized by a particular process it undergoes in the DES it enters. For instance, in a computer system there may be two different job types that follow different processes.

**Attributes**: Information characterizing a particular individual entity of any type. Thus, we usually attach a unique record to each entity that consists of this entity's attributes (example, for a part in a manufacturing system, attributes may be the part's arrival time at the system, its type, and its 'due date', that is, the time by which it is required to leave the system).

**Process Functions**: The instantaneous actions or time delays experienced by entities.In general, a process can be represented as a sequence of functions. A functions is one of two types:

1. Logic functions: Instantaneous actions taken by the entity that triggers this function in its process. For example, checking a condition such as "is the server idle?" or updating a data structure, such as recording the arrival time of the entity.

2. Time delay functions: The entity is held by that function for some period of time. There are two types of time delay functions:
    a. Specified time: The delay is fixed, usually determined by a number obtained by the Random Variate Generator used in the simulation. For example, a service time that depends only on some prespecified service time distribution. This terminology is also called "**activity**".

    b. Unspecified time: The delay depends on the state of the system. For example, the time spent waiting in a queue until the entity can seize a server. This terminology is also called "**delay**".

**Resources**: Objects providing service to entities (example, machines in a manufacturing system, processors in a computer system, switches in a telephone network). Time delays experienced by an entity are due to either waiting for a particular resource to be made available to that entity, or receiving service at that resource.

**Queues**: A collection of (permanently or temporarily) associated entities ordered in some logical fashion (such as all customers currently in a waiting line, ordered by first come, first served, or by priority)., usually the fact that they are all waiting for the use of a particular resource. An entity flowing through the system is always located in some queue unless it is in the process of being served by a resource. This terminology is also called "**list**".

**Event**: An instantaneous occurrence that changes the state of a system, such as the arrival of a new customer.

### 3.2.2 Examples of DES languages

**GASP**

GASP is a collection of over 30 FORTRAN routines that can be used to simplify the process of building a simulation based on *event scheduling scheme*. It is usually available on computer systems that support FORTRAN, see Pritsker and Kiviat, [PritskerK 69].

**GPSS, GPSS/H, GPSS/PC**

GPSS (General Purpose Simulation System) was originally developed by Gordon at IBM in the early 1960s. Since then it has evolved, with the most recent version , GPSS/H, developed at Wolverine Software, see Schriber [Schriber 90]. GPSS/H is a language based on "blocks" with which one can build *a process-oriented simulation* model. Entities are referred to as "transactions", and attributes as "parameters". Using standard graphical representations of the more than 60 basic blocks, one can conveniently define a model in terms of a block diagram for most systems of interest. A version of GPSS/PC, specifically designed for PCs is also available through Minuteman Software.

**SIMAN**

SIMAN (SIMulation ANalysis) was developed by Pegden in the early 1980s and is recently available through System Modelling Corporation, see Pegden *et. al.,* [PegdSS 95] and [PegdSS 91]. It allows one to use the process-oriented scheme, the event scheduling scheme, or a combination of both. Like GPSS/H, a process is built in terms of basic blocks which can also be combined through their graphical representations to construct a block diagram. A newer version of SIMAN called ARENA allows one to animate a simulation on screen on most common computer operating systems, including PCs.

**SIMSCRIPT**

Like SIMAN, SIMSCRIPT has both process-oriented and event scheduling scheme capabilities. However, the former are sufficiently general so as to render the latter unnecessary for most applications. SIMSCRIPT was developed by Markowitz at the

Rand Corporation in the early 1960s. The most recent version is available through the CACI Products company, see Kiviat [Kiviat 69]. The generality and free format style of SIMSCRIPT make it particularly attractive for modelling complex systems which do not need to be characterized exclusively by a queuing structure.

**SLAM**

SLAM (Simulation Language for Alternative Modelling), like SIMAN and SIMSCRIPT, provides both process-oriented and event scheduling scheme capabilities. SLAM was developed by Pegden and Pritsker in the early 1970s and is available through the Pritsker Corporation, see Pritsker [Pritsker 86]. In SLAM, the modelling process usually involves a network definition of the system consisting of "nodes" and "branches", which can be done graphically, SLAMSYSTEM and SLAM II/TESS are versions that provide animation and graphical sensation of output reports.

**EXTEND**

EXTEND is an object-oriented simulation package with extensive libraries of "objects" for different applications. It allows the user to "extend" these libraries by building new objects (that is, model building blocks) through simple C-based templates. It also provides the ability to construct hierarchical models and includes a variety of plotting and graphical output analysis tools, as well as animation.

This is only a brief and partial account of available discrete-event simulation software. There are several additional simulation languages (for example, SIMPAS, SIMULA, DEMOS, SIM++), and some specifically geared towards particular types of discrete-event simulation, such as manufacturing, (for example AutoMod, Taylor II, ProModel, WITNESS, AIM, SIMFACTORY) and computer networks. With the recent emergence of object-oriented programming and parallel processing capabilities, it is likely that a new generation of languages or new versions of existing ones will be developed.

Details descriptions and comparisons of simulation languages are provided in [Banks, Carson and Nelson 1996 [Banks 96], and Law and Kelton 2000 [LawK 00].

## 3.3 Developing a simulation model

Pidd [Pidd 98], regarded modelling as "*a learning process that proceeds gradually in a parsimonious manner*". He suggested that " *a model should be developed gradually, starting with simple aspects that are well understood and moving step-by-step towards a more complete representation*".

This work is devoted towards the development of a simulation model for a supply chain system. To guide the development of a simulation model using a DES environment, several approaches, as proposed by many authors, have been used. Figure 3-1 shows the flow chart representation of the steps undertaken in the modelling process that have been evolved during this investigation. Similar figures and interpretation can be found in other sources such as Law and Kelton [LawKe 91], Pegden, Shannon, and Sadowski [PegdShSa 95], Banks, Carson and Nelson [BankCaNe 98], and Balci [Balci 98].

In modelling a supply chain, two main features have to be modelled: the resource flows, and the modelling of the arrival of orders or messages which shall be regarded as a feedback process. The modelling consists of two separate phases: development phase and experimental phase.

**DEVELOPMENT PHASE:**

- **Problem Formulation ($\Delta G_p$):**
  Provide a detailed description of the supply chain system as in the actual situation.

- **Setting of Objectives :**
  Specify the aim and objectives of the simulation study, and what are to be achieved and understood.

- **Conceptual Model ($\Delta G_c$):**
  Develop a structured conceptual model to mimic the supply chain system in a computer simulation, as described in the problem definition.

- **Implementation Model ($\Delta G_m$):**
  Develop the computer model (i.e., coding into operational model).

- **Verification:**
  Compare the conceptual model to the computer model that implements the conception. Refine until $\Delta G_m = \Delta G_c$.

- **Validation:**
  Compare the model's behaviour with the system behaviour through computer simulation. Refine the computer model until its behaviour matches the behaviour given in the problem formulation to an agreed level of accuracy. Is $\Delta G_m = \Delta G_p$ ?

**EXPERIMENTAL PHASE:**

- **Experimental Design:**
  Specify the problems and scenarios to be analysed (test out different decision policies).

- **Simulation and Evaluation of Results:**
  Evaluation and re-design of the order policies and investigate other alternatives.

- **More Simulation Runs:**
  Do more runs to get meaningful results.

- **Documentation:**
  Presentation and documentation of results.

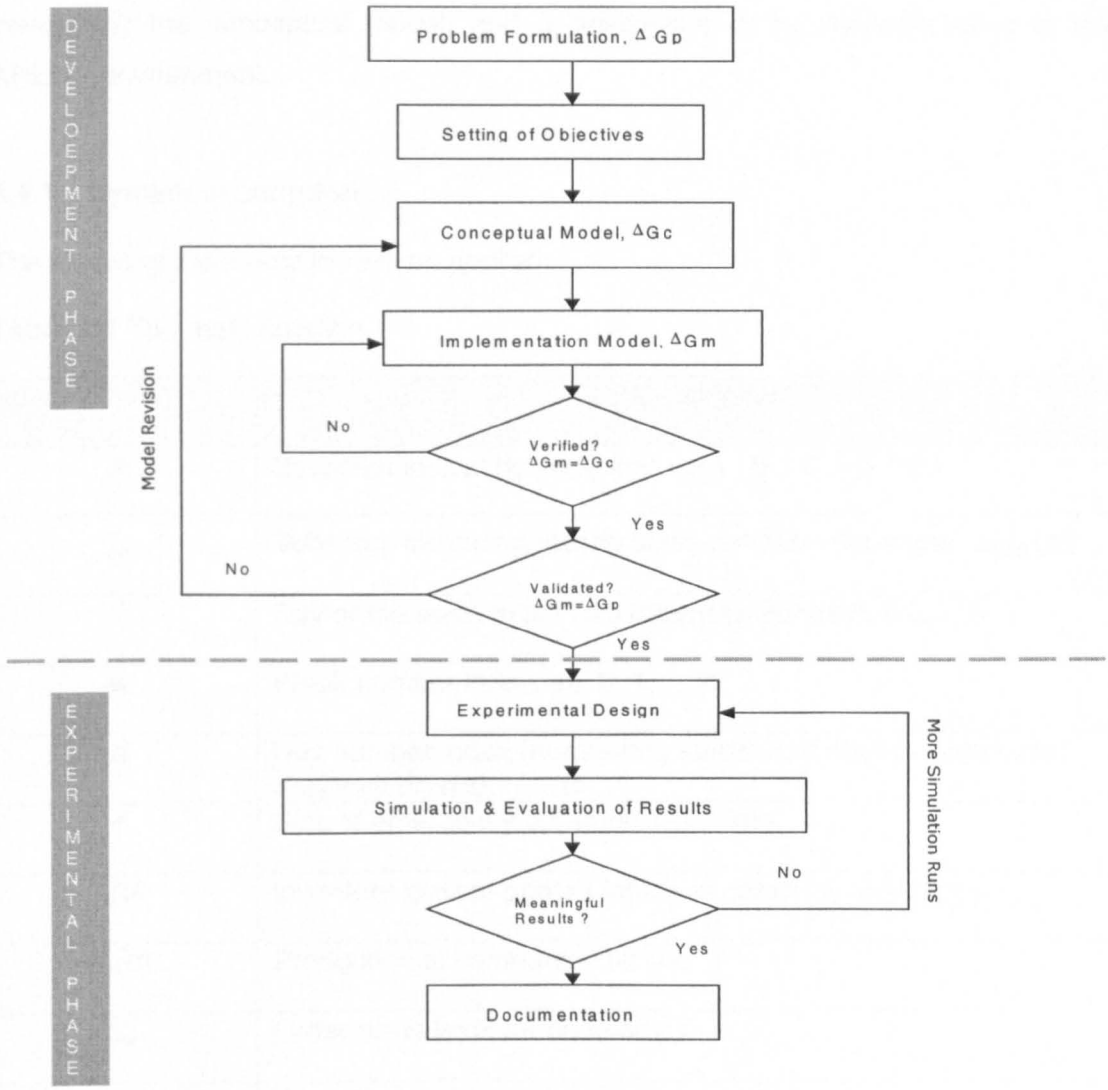



**Figure 3-1** A flow chart representation of the modelling steps

## 3.4 The supply chain system

This section describes the development of a simulation model of a supply chain system based on a fast moving consumer goods (FMCG) supply chain producing to order with random fluctuations in demand patterns. A detailed problem formulation

based on the system components and its behaviours, designed for the purpose of this study is presented. Next, the objectives indicating the questions that are to be answered by this simulation study is specified. This is followed by a discussion on developing the conceptual model, and a description of its implementation in the ARENA environment.

### 3.4.1 System description

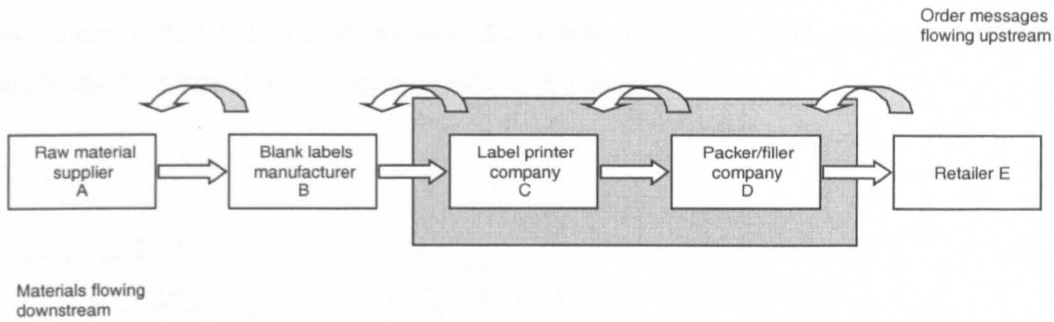
The following main notation will be applied:

**Table 3-1** The main notation

| Notation | Description |
|---|---|
| $x$ | Subscript indicating company $x$={A \| B \| C \| D \| E } |
| $ss$ | Subscript indicating steady state condition (example, $u_{Ess}(d)$) |
| $i$ | Day of the week index ($i=0$ indicates Sunday), $i$=0,…,6 |
| $w$ | Week number index, $w$= 0, 1,…,$W$ |
| $d$ | Day number index (numbering starts from start of simulation) $d=(7w+i)$ or, $d$=0,1,…,$D$ |
| $e$ | Size of emergency order sent to printer |
| $l_x(d)$ | Inventory level of printed labels at company $x$ on day $d$ |
| $p_x(d)$ | Production at company $x$ on day $d$ |
| $S_x$ | Order-up-to-level for company $x$ |
| $s_x$ | Re-order level for company $x$ |
| $ss_x$ | Minimum stock level for company $x$ |
| $u_x(d)$ | Order placed by company $x$ on day $d$ |
| $V_D(w)$ | Average variation in weekly orders placed by company D measured at week $w$ |
| $y_x(d)$ | Goods delivered by company $x$ on day $d$ |

Additional notation will be introduced as the need arises.

Figure 3-2 is a description of the representative model illustrating the relationship between the companies in the chain, the end product of which is the supply of boxes of fresh vegetables to a retailer.




***Total lead times:***
Raw material supplier to blank labels manufacturer: 3 days.
Blank labels manufacturer to label printer company: 3 days.
Label printer company to packer/filler company: 3 days
Packer/filler company to retailer: 17 hours.

***Internal model:***
Company D: A single production machine which runs for an 8 hour shift. There is an inventory store for the labels.
Company C: One machine which is used to print labels and can produce 100 units per hour and operates one shift of eight hours each day. There are two inventory stores. a. for blank labels, and b. for finished printed labels (acts as an intermediate buffer).
Company B: One machine which is used to produce customised blank labels. There is a single inventory store to hold paper and substrates.

**Figure 3-2.** A schematic diagram of the FMCG supply chain.

Company A, the raw material supplier, supplies both paper and laminate to company B who produce rolls of blank labels. It is assumed that the adhesive is always available. Company B, the blank labels supplier, produces rolls of sticky labels (in customized sizes) from larger rolls of paper and adhesive. The blank substrate is supplied to company C, the label printer, who print, cut and supply label rolls to company D, the packer/filler. Company D is a large co-operative fresh produce company who, in addition to growing their own produce, purchase from a number of market gardeners and overseas companies. Company D packs and labels the product and supplies it to the distribution centre for company E, the retailer. Company E on receiving the ordering information from their stores will initiate the demand for boxes of fresh vegetables, and provides this information to company D. A regular order of 100 units is placed at 7.00 am each day, for delivery between 10.00 pm and midnight on the same day.

In this problem, specifically, we are more interested in the dynamics of the label printer company and the packer/filler company. Thus, the retailer will be treated as a constraint (disturbance to the system). In the same sense, the label manufacturer (company B) can be treated as a constraint (disturbance): in situations such as if the label manufacturer is unable to provide sufficient supply, and also considering the lead times of three days being imposed to the system.

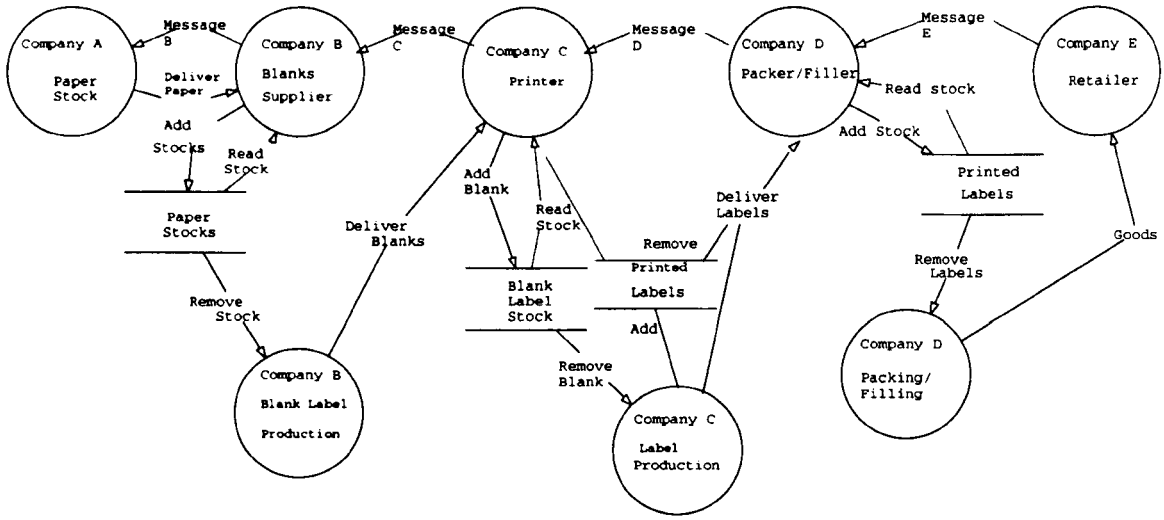



**Figure 3-3** A description of the interactions between companies and their internal structures.

Figure 3-3 gives a detailed description of the interactions between companies and each of their internal structures.

### 3.4.2 Problem formulation (the model description)

In addition to the description given in section 3.4.1, the following assumptions are also specified.

- **Company E: Retailer**

At steady state, the order from retailer (E) to packer/filler (D) $u_{Ess}$ (d) = 100 units per day.

- **Company D: Packer/filler**

- ***Production and Inventory***

Assume a single production machine which run for an 8 hours shift. The set-up time, $t_s$, is 0.6 hours. The maximum capacity of the machine is that it can produce 100 units per hour and operates one shift of eight hours each day. Loading onto lorries is a parallel operation and need not be modelled. Assume there is a single inventory store. Assume that printed labels are held on rolls of size equal to 10 units of product.

- ***Ordering policy***

The scenarios for company D is as follows:

Minimum stock level (safety stock level) at packer/filler $ss_D = 300$.

Re-order level at packer/filler $s_D = ss_D + LT \times D$ units/day = 600, where LT is the lead time delays which equal to 3 days, and $D$ is the nominal demand from retailer.

Order from packer/filler (D) to printer (C) is issued once per week $u_D = 700$ units. The order is sent on day $i = 0$, that is Sunday. [Fixed weekly order at fixed interval].

Mathematically, this can be written as $u_D(d) = u_{Ess}(d) * 7 = 700$

On any other day, if stock falls below a certain threshold value, defined as $s_{D\,threshold} = (S_D - (ss_D - u_E(d))$, an order will be placed to replenish stock.

Mathematically, the order amount $e = 7^* u_E(7w+i) - l_D(7w+i)$, where $l_D(7w+i)$ is the *current stock level.*

The orders may be sent with a maximum of three days delivery. That is an order sent on day $d$ before 5 pm must be delivered by 5 pm on day $d$+3.

The decision policy at the company D is as follows:

*If day is Sunday (day.eq.0), order a fixed quantity of* $Q_D = 7^* u_{Ess}(d)$ *units.*

*If day.ne.Sunday, and stock + quantity on order .le.* $(S_D - (ss_D - u_E(d))$, or

$$l_D(d) + \sum_{i=0}^{d}[y_C(i) - u_D(i)] \leq s_{D\,threshold}$$

*make an order for quantity,* $e = 7^* u_E(w+i) - l_D(7w+i)$ *to replenish the stock level.*

- **Company C: Printer**

- ***Production and inventory***

The set-up time is two hours. Printer can produce 100 units per hour and printer operates 1 shift of 8 hours each day. If demand is greater than 800 units, the production will continue the next day. A lead-time commitment of three days was made to the packer/filler as a condition of supply, that is delivery delay printer to packer/filler is 3 days. The management prefers to produce in a large batch and at a fixed interval.

- ***Order policy***

Company C replenishes its stock using an order-up-to-production policy denoted by a heuristic $(s,S)$ policy. This is similar to a $(s,Q)$ policy since the quantity order is always fixed.

For modelling purposes, the values for $S_C$ and $s_C$ are calculated as follows:

$s_C$ = Lead time demand (LTD) + safety stock,

$s_C$ = 700 *2 + 700 * 1.5 = 2450 units (making assumption that a lead time demand of 2 weeks supply for packer/filler, and safety stock of 1.5 * regular weekly orders from packer/filler).

$S_C$ = 4900 ( making the assumption that $Q_C$ , the order quantity, equals 2450 units).

Therefore, $S_C$, the order-up-to-level = 4900, $s_C$, the re-order point = 2450, and the order quantity, $Q_C$ = 2450 units.

The decision policy at the printer company, C, is stated as follows:

*If stock + quantity on order .le. $s_C$, then order $Q_C = S_C - s_C$*

- ***Additional information***

In addition to the blank labels stock, there is also a buffer stock of printed labels in company C to hold a stock of printed labels. The quantity is typically between 100 and 200 units. The inventory policy is that sufficient labels are held in stock to meet needs of a sudden increase in order from packer/filler.

The blank label stock will be in rolls of fixed size and will be able to produce a set number of printed labels. The decisions about operation for modelling purposes have to consider whether to print *p* units and take 100 units from the buffer stock, or to print *q* units and add 100 units to stock.

The control decision is as follows:

*If buffer stock.le.100 units, print* $p_C(d) = y_D(d) + 100$ *units and add 100 units to buffer stock.*

*If buffer stock.ge. 200 units, print* $p_C(d)=y_D(d)-100$ *units and take 100 units from buffer stock.*

- **Company B: Blanks label supplier**

- ***Production and Inventory***

The company has one machine and operates with three shifts seven days each week. The lead-time for customising the laminate is three days from order.

- ***Order policy***

Company B replenishes its stock using an order-up-to-production policy denoted by a heuristic (*s,S*) policy. This is similar to a (*s,Q*) policy, since the quantity ordered is always fixed.

For modelling purposes, the values for $S_B$ and $s_B$ are calculated as follows:

$s_B$ = LTD + safety stock,

$s_B$ = 2450 *2 + 2450 * 1.5 = 8575 units, and is rounded to 8600 units (making an assumption that a lead time demand of 2 weeks supply for packer/filler, and safety stock of 1.5 * regular weekly orders from packer/filler).

$S_B$ = 17200 ( making the assumption that $Q_B$, the order quantity, equals 8600 units)

Therefore, $S_B$, the order-up-to-level = 17200, $s_B$, the re-order point = 8600, and the order quantity $Q_B$ = 8600 units.

The decision policy at the blanks label company, B, is,

*If stock + quantity on order .le.* $s_B$, *then order* $Q_B = S_B - s_B$

- **Company A: Raw material supplier**

Company A is assumed be able to provide a continuous supply of raw materials to company B.

Table 3-2 summarised the parameters used in the base model.

**Table 3-2** Parameter values for Base model.

| [a]Raw material supplier, A | Blanks supplier, B | Printer, C | Packer/filler, D | Retailer, E |
|---|---|---|---|---|
| Provide a continuous supply of materials | $(s,S)$ policy, or an (s,Q) policy since $Q_B$ is fixed. | $(s,S)$ policy, or an $(s,Q)$ policy since $Q_C$ is fixed. | Ordering decision (For the base model, this is to be called generic policy) | Send order with values $u_E(d)$ =100 units |
| | $S_B = 17200$ | $S_C = 4900$ | Weekly order: $u_D(7w+i) = 7\ u_{Ess}$, for i =0 | |
| | $s_B = 8600$ | $s_C = 2450$ | Emergency order: $u_D(7w+i) = e,\ i \neq 0$ where $e =$ $7\ u_E(7w+i) - I_D(7w+i)$ | |
| | $ss_B = 3700$ | $ss_C = 1050$ | | |
| | $Q_B = 8600$ | $Q_C = 2450$ | | |

*Note*:

[a] Ordering decision is not included in the model

In the context of this work, the purpose is to develop a supply chain management production-inventory control simulation model, to be called the *'Base model'*, implemented on DES software ARENA.

### 3.4.3 The study objectives

The aim of this part of the research is to develop a supply chain management production-inventory control model, based on the given description (section 3.4.2), implemented on a DES software ARENA, for the following objectives:

a) to investigate the necessary details required to produce a 'sensible model" (the model granularity) of a supply chain (based on a particular case in a packaging industry supply chain) on a DES simulation environment.

b) to propose a suitable approach in modelling a supply chain using DES language, and applying this approach in building a simulation model, to be called the base model. The approach to be taken is summarised as follows:

- Conceptualisation
- Implementation
- Verification, and
- Validation.

Conceptualisation includes the construction of sequence diagrams to aid in visualising and documentation of the system's dynamic behaviour.

It is worthwhile to mention here that in later work, the base model that has been developed will be used as an experimental tool to investigate several issues related to this particular supply chain.

In the following section the modelling issues to be considered in the modelling stages is discussed. Section 3.5 and 3.6 discuss the design and development of the supply chain simulation model associated with ARENA simulation language. The validation and verification activities conducted will be discussed in Chapter 4.

## 3.5 Modelling issues

The first part of this section discusses the issue on the details sufficient to model a supply chain system. The second part, discusses the issue related to the discrete-event simulation model representation, and on the modelling of a supply chain system. The aim of this section is to give a general coverage on these issues and the proposed solutions for achieving a sufficiently accurate and sensible model of the system.

### 3.5.1 Minimum details for modelling a supply chain

Supply chains involve complex operations and their analysis requires carefully defined approach. It is easy to get lost in details and spend a large amount of effort in analysing the supply chain. On the other hand, it is also possible to execute too simplistic an analysis and miss the critical issues. It is easy to simulate at a level of detail that does not match the objective of the analysis: for example, a highly detailed simulation model is built than that required for the objectives of the analysis.

Jain *et. al.*, [JainCWE 01] pointed out that the appropriate level of details in a simulation model designed to answer a certain question is somewhat subjective. They highlighted that the level of abstraction chosen for modelling purposes is also influenced by several other constraining factors such as data availability, expertise of the modeller, simulation software capabilities, and time availability.

In the context of this work, the simulation model should have an easily modifiable structure so that inventory managers (decision-makers) at company C (the printer), and company D (the packer/filler) could evaluate the several 'what if' scenarios and be able to furnish them with some valuable understanding of the supply chain system.

The following two features describe the level of details (level of abstraction) required for this particular problem.

- The model behaviour should be explicitly defined:
  Each echelon (company) is represented by a number of sub-models. For example echelon C, the label printer, will be represented by its sub-models consisting of

the production site, inventories, and a 'managerial unit', which can make active decisions. The later is 'reactive' to the order (message) and should be able to coordinate the flow of system entities (materials) through the processes. The managerial unit can be modelled by having rules for how it will react to events, that is, to model it as a sequence of rules (representing the order policy).

- The model inputs and outputs should be explicitly defined:
  The reading of data from an input file (for example, a stream of data from a text file) that represents the order arrivals from the end customer, should be made available. The writing of output data (results) to an output file (for example, Excel) for graphical representation of the order/demand quantities, the inventory levels, and the production rates at a particular facility of interest over a period of time, should also be available. These observations could then be analysed, and consequently the true system (supply chain model) performance measures can be estimated. The information gathered can be used to evaluate and redesign the supply chain parameters, for example the inventory policy.

A more detailed discussion will be given in section 3.6: the development of the conceptual model.

### 3.5.2 Modelling a supply chain with DES

In [Banks 98], Banks distinguished the differences between a discrete-event simulation model and other types of simulation models, by stating that a *"discrete-event model attempts to represent the components of a system, including a detailed representation of the internals of the model, and their interactions to such an extent that the objectives of the study are met"*.

This is in contrast with most mathematical, statistical, and input-output models which *"represent a system's inputs and outputs explicitly, but represent the internals of the model with mathematical or statistical relationships"*.

A model built based on a discrete-event simulation environment can grow excessively as more system components and its internal models are added. Obviously, the model

should be kept simple but should include all the aspects of systems relevant to the study objectives.

The DES simulation tool as originally designed for use in simulating manufacturing systems, is a very useful approach in evaluating resource flows (such as machinery, people, materials). The modelling will usually require the tracking and controlling of the flow of system entities through several stages of production facilities, and normally these entities are transformed into new products (parts) as they undergo the various processes.

In modelling a supply chain, there is a vital requirement to model the arrival of orders or messages (upstream flow of orders or messages), which shall be regarded as a feedback process. However, the modelling of orders has rarely been addressed due to the fact that a DES tool is intended for use in attacking a direct (feed-forward) process oriented problem similar to the manufacturing system. Due to the above reasons, it is helpful to devise a scheme to guide the development of a sufficiently accurate model.

The following summarises the scheme formulated for successful modelling of the supply chain system:

- To assume that the system entities are essentially passive and do not take decisions about routes and destinations.
- To treat each echelon as being 'reactive' to the flow of orders (messages).
- To treat each echelon being as able to coordinate the flow of system entities (materials).
- To create the logic and mathematical relationships that is sufficient to describe the situation to be modelled.
- To create a viable mechanism to correlate the logical and mathematical relations and the dynamics of the orders (messages) between the echelons, and the flow of system entities through the echelons.

In acknowledgement to the complication of modelling a supply chain on a DES tool as described above, it is necessary at the initial stage to develop a conceptual model

for the system. This conceptual model will become a basis in building an implementation model using ARENA simulation language.

In building the conceptual model the following elements to aid the development phases has been recognised:

- Defining the system's behaviour explicitly.
- Developing system's inputs and outputs explicitly.
- Modularity approach to allow scalability and reducing model complexity.
- Mechanism to facilitate the coordination of entities flow.

## 3.6 The conceptual model

In this section, the design of a conceptual model of the supply chain system is presented. The conceptual model is simply a list of elements that are to be included in a model and the detail required for each of these elements including the relationships between them (for example, control rules and flow of elements). The conceptual model is formulated to be independent of any programming or simulation language, see Brooks and Robinson [BrooksR 01].

### 3.6.1 Define the system's behaviour explicitly

The first step in the conceptualisation phase is to identify, express and modify the supply chain system directly in terms of its behaviour. The structural properties of the system that is sufficient to describe its behaviour can be itemised as follows:

- Each echelon (company) is represented by a number of sub-models. For example echelon C, the label printer, will be represented by its sub-models consisting of the production site, inventories, and a 'managerial unit', which can make active decisions. The later is 'reactive' to the order (message) and is able to coordinate the flow of system entities (materials) through the processes. The managerial unit can be modelled by having rules for how it will react to events, that is, to model it as a sequence of rules (representing the order policy).

- The orders (messages), as a means of communication between the echelons behave as feedback signals.
- The system entities, for example the raw material, behave as the objects that change states (attributes) as they move through the system. These systems entities will be processed and transformed into new products (that is, assigned with new attributes) as they are being directed downstream from one echelon to the next echelon.
- Each echelon will be assigned with a different time bucket to resemble the actual system. To model the communication (information exchanges) between the echelons, initially the following assumptions will be made: the order (message) from echelon E to echelon D is being fedback daily, the order (message) from echelon D to echelon C will usually be delivered on a weekly basis, followed by normally a forth-nightly basis for the order (message) to be passed upstream from echelon C to echelon B, and for the most part on a monthly basis for a message to be delivered from echelon B to echelon A.

### 3.6.2 Develop system's inputs and outputs explicitly

The next step in the conceptualisation phase is to design the model according to the requirement that it will be utilised as an experimental tool to allow the study of some production-inventory control methods on the whole supply chain system. Hence, the following features have to be provided:

- Reading from an input file (for example, a stream of data from a text file) that will represent the order arrivals from the end customer. This stream of data is read directly into the simulation model in order to generate events at the time specified in the model.
- Writing output data (results) to an output file (for example, Excel) for graphical representation of the order/demand quantities, the inventory levels, and the production rates at a particular facility of interest over a period of time. These observations could then be analysed, and consequently the true system (supply chain model) performance measures can be estimated. The information gathered can be used to evaluate and redesign the supply chain parameters.

### 3.6.3 Mechanism to facilitate the co-ordination of entities flow

The next following step in the conceptualisation phase is to define the mechanism to facilitate the coordination of the flow of products (materials) in an efficient manner with the use of messages. For instance, the controlling of the flow of system entities (products) could be addressed by manipulating the available order information (for example, the quantity to order) together with the information from each facility (for example, the inventory level) upon the occurrence of a certain event at a particular point in time. Some specific signals will be made active and based on specified conditions would able to trigger (activate) certain processes. Hence, the following features (functional elements) have to be made available:

- The supply chain model is dynamic and stochastic. Hence, the passage of time plays a crucial role. Therefore, a central time reference (clock) sub-model to enable events and activities to be referred to a standard time reference is needed. This function is vital since the timing of the system's sub-models have to be effectively synchronised.
- A localised logic decision sub-model, which is a component of the 'managerial unit', is needed to generate the ordering messages. This message is generated with the proper correlation of the logical and mathematical relations of the available information from the facilities. For example, a message on the number of products required is generated in each echelon at a regular time (for a usual weekly order) or at a random time based on the ordering policy and the inventory level at a particular facility.
- A localised logic decision sub-model, which is a component of the 'managerial unit', is needed to manipulate the downstream information to control the upstream activities. This sub-model has the tasks of processing information (order quantity, inventory level, etc.) and generates specific instruction (in the form of a signal) to other sub-models (production site, inventory, etc.) to trigger (execute) the controlling of flow of system entities. For example, everyday the model will track the inventory level at echelon D. If this level falls below a specified level, a control signal is generated to trigger (notify) echelon C to send more materials (printed labels). Once echelon C has received this signal, a specified amount of materials

(blank labels) in inventory C will be transferred to the production facility in C to undergo production.

- A sub-model that functions as a routine to inform of when to access (read) an order message is needed. For example, the ordering message from echelon E to echelon D is read every day, at 07.00 hours.
- A sub-model that functions as a routine to determine of when to assign (write) a new data (order information) is needed. The information is conveyed to the production facility at a regular interval. For example, the quantity as demanded by echelon E is to be made available to the production facility of echelon D at 08.00 hours every day.

### 3.6.4 Modularity approach for scalability and reducing model complexity

The next following step in the conceptualisation phase is to adopt the concept of 'modularity', which is important for re-deploying the frequently occurring sub-models. This is useful for the purpose of reducing the amount of time needed to build the implementation model, that is by decomposing the model into its sub-models, making it simpler to implement. With some modification in the parameters (variable names, values, and etc.), a sub-model representing an inventory at echelon D can be deployed again in modelling similar inventory at other echelons.

Hence, the following modelling routines (sub-models) are developed:

- Sub-model: Inventory.
- Sub-model: Production.
- Sub-model: Generate order policy and coordinate entities flow.
- Sub-model: Reading from a data file.
- Sub-model: Writing to a data file.

In addition to the benefit of reducing the amount of time required to build the implementation model, this modularity approach offers better model tractability, ease of debugging, provide scalability for model expansion, as well as reducing model complexity. To aid in transforming the conceptual model into the implementation

model, an interaction diagram to address the dynamic view of the system is to be constructed.

### 3.6.5 Sequence diagrams

In visualising the dynamic behaviour of a system, in this case a supply chain system, for the most part, this requires the modelling of states and objects along with the messages that are dispatched between them. The documentation of the dynamic aspects of the system is one of the major steps in aiding the programmer to construct and implement the model in a DES.

A sequence diagram is one of the several types of interaction diagrams that is used for modelling the dynamic aspects of a system, that emphasis the time ordering of messages. An interaction diagram shows an interaction, consisting of a set of objects and their relationships, including the messages that may be dispatched among them. Graphically, a sequence diagram is a table that shows objects arranged along the x-axis and messages, ordered in increasing time, along the y-axis. See [BoochRJ 99] and [Douglass 98].

In these diagrams, the physical components are denoted as objects. The supply chain system is divided into the following physical components (objects):

- the retailer,
- the packer/filler company consisting of packer/filler management, packer/filler printed label stock, and packer/filler production,
- the printer company consisting of printer management, printer blanks stock, printer production, and printer printed label buffer stock,
- the blank supplier company consisting of the blank supplier management, paper stock, and blanks production,
- the raw material supplier.

Figures 3-4, 3-5, and 3-6, show the sequence diagrams that have been developed during this part of the modelling. In this study, the sequence diagrams have been constructed for the following cases:

- ***Retailer places order:***

Company E (retailer) on receiving the ordering information from their stores will initiate the demand for boxes of fresh vegetables, and provides this information to company D (packer/filler). The order is placed each day at 7.00 am each day for delivery between 10.00 pm and midnight on the same day.

Figure 3-4 shows the detailed sequences of messages between the states, for retailer and packer/filler companies.

- ***Packer/filler places order:***

On Sunday, order a fixed quantity of $7^{*}u_{Ess}$. On any other day, if stock falls below a certain level, an order will be placed to replenish stock. Every order is placed at 8.00 am. The orders may be sent with a maximum of 3 days delivery, and the delivery is expected before 5 pm on the third day after receipt of order.

The decision policy at the company D is as follows:

*If day is Sunday (day.eq.0), order a fixed quantity of* $Q_D = 7^{*}\ u_{Ess}(\mathrm{d})$ *units.*

*If day.ne.Sunday, and current stock + quantity on order .le.* $s_{D\ threshold}$ *, make an order for quantity,* $e = 7^{*}u_E(w+i)$ *– current stock level to replenish the stock level.*

Figure 3-5 shows the detailed sequences of messages between the states, for packer/filler and printer companies.

- ***Printer company places order:***

Company C sends orders for blank labels as and when it requires them. Every order is placed at 8.00 am. Delivery from company B is 3 days of receipt of order, and is expected before 6.00 am. Company C replenishes its stock using an order-up-to-production policy denoted by a heuristic $(s,S)$ policy, where, s, the order-up-to level = 4900, and S, the re-order point = 2450. Detail calculation is given in section 3.4.2.

The decision policy at the printer company, C, is stated as follows:

*If stock + quantity on order .le.* $s_c$*, then order* $Q_C = S_C - s_C$

- ***Additional Information***

Besides the blank labels stock, company C also holds a buffer stock of printed labels. The volume of this stock is to be between 200 units, and 100 units. If the buffer stock .le. 100 units, request for refilling. If the buffer stock.ge. 200 units, release stock if requested in the rules (inventory policy, or decision policy). Detail calculation, and decision rules is given in section 3.4.2.

- ***Blanks supplier company places order:***

Company B sends orders for raw material (paper and substrates) as and when it requires them. The order is send at 8.00 am and the delivery is expected before midnight on the same day. It replenishes its stock using an order-up-to-production policy denoted by a heuristic $(s,S)$ policy, where, $s$ or $s_B$ , the order-up-to-level = 17200, and $S$ or $S_B$, the re-order point = 8600.

The decision policy at the blanks label company, B, is,
*If stock + quantity on order .le.* $s_B$, *then order* $Q_B = S_B - s_B$

It is assumed that, company A is providing a continuous supply of raw materials to company B.

Figure 3-6 shows the detailed sequences of messages between the states, for printer, blanks supplier, and raw material supplier companies.

The point of time of when the simulation measurements is to be made is indicated by markers (M1,...,M11). The time 9.00 am is chosen as the time to read the simulation measurements, based on the following observations:

- To read the stock values when it is at the lowest points, during the time between 8 am and 5 pm,

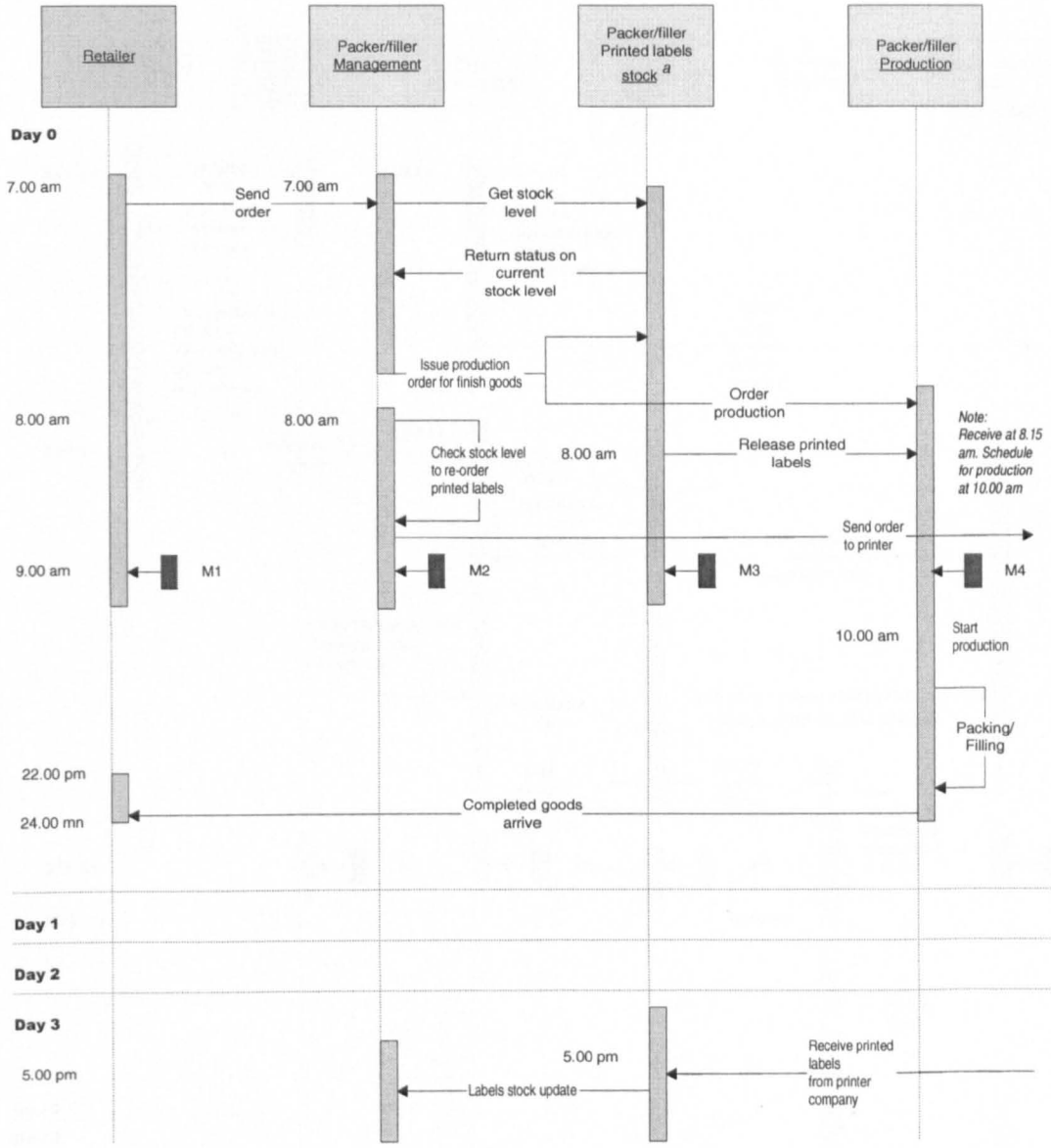
- To avoid reading at a later time, say 4.00 pm because the output of the simulation could exhibits large variations (since it will be difficult to separate variations over time) when there is a stock-in earlier (say at 4.00 pm) than at the normal stock-in time (at 5.00 pm).

- To avoid any problems of calculations, during the validation stage.

**Table 3-3.** Simulation markers nomenclature

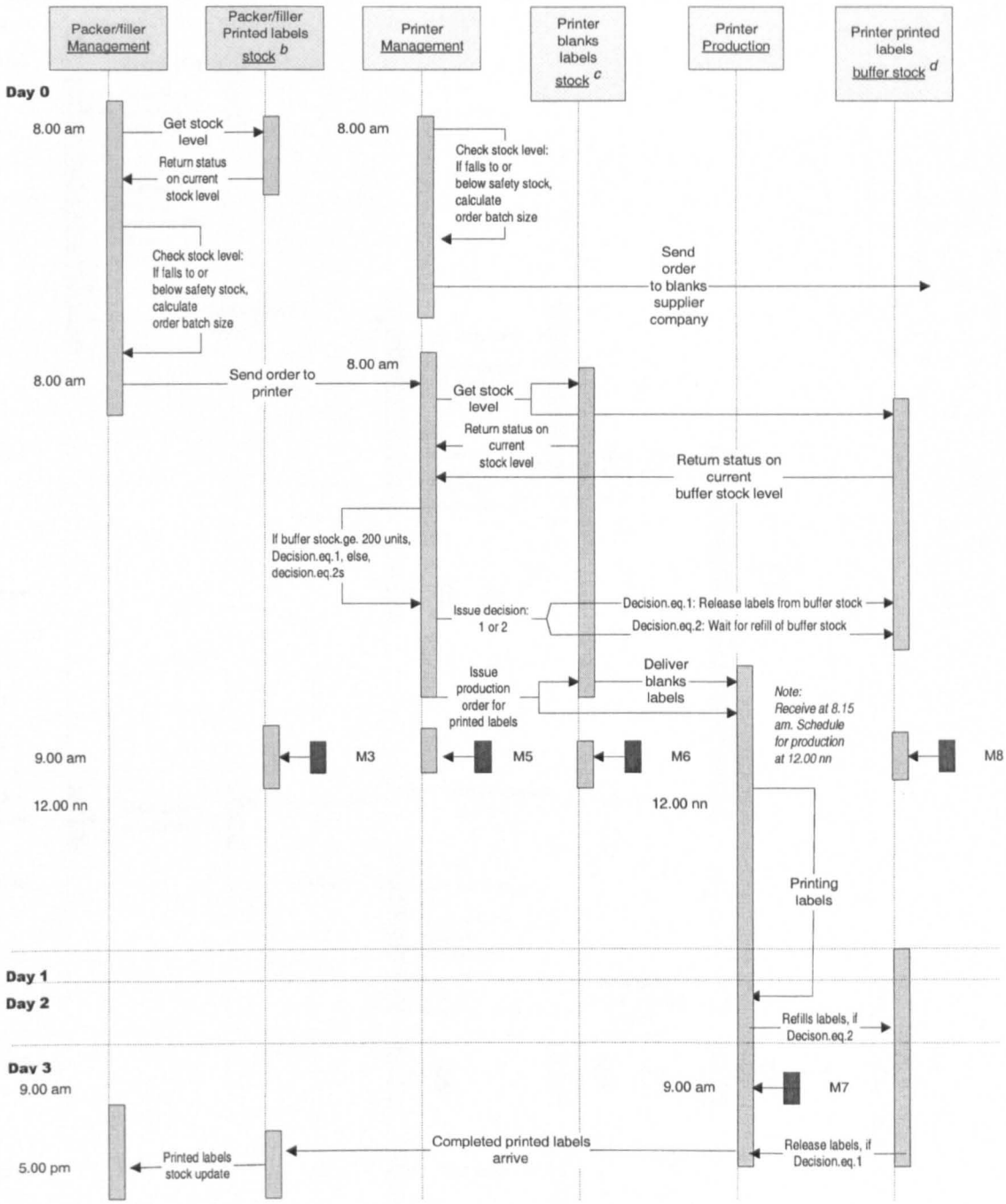
| Marker | Description |
|---|---|
| M1 | Read order quantity issued by Retailer |
| M2 | Read order quantity issued by Packer/filler |
| M3 | Read stock level at Packer/filler printed labels stock |
| M4 | Read production size at Packer/filler production machine |
| M5 | Read order quantity issued by Printer |
| M6 | Read stock level at Printer blanks labels stock |
| M7 | Read production size at printer production machine |
| M8 | Read stock level at Printer printed labels buffer stock |
| M9 | Read order quantity issued by Blank supplier |
| M10 | Read stock level at Blanks supplier paper stock |
| M11 | Read production size at Blanks label production machine |

Simulation markers as described in Table 3-3 are used as indicators to mark on the sequence diagrams in Figure 3-4, Figure 3-5 and Figure 3-6, the points of time when the simulation measurements are made.



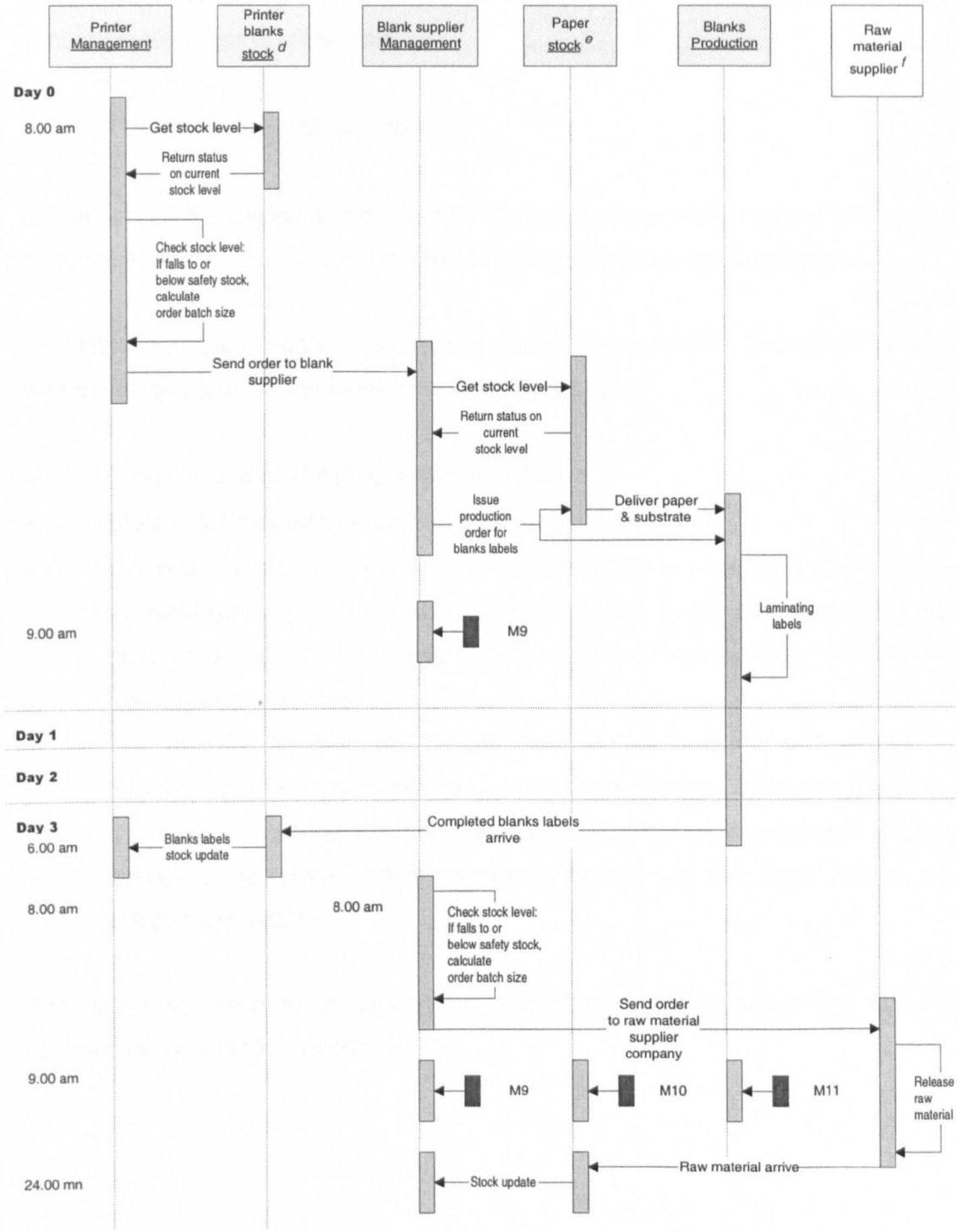

*Note:*
Details for Day 1 and Day 2 is shown in Figure 3-5.
[a] Based on the assumption that the stocks have been filled with some initial quantities

**Figure 3-4** Sequence diagram for the retailer and the packer/filler companies.




*Note:*
*b, c, d* Based on the assumption that the stocks have been filled with some initial quantities

**Figure 3-5** Sequence diagram for the packer/filler and the printer companies.




*Note:*
*d, e, f* Based on the assumption that the stocks have been filled with some initial quantities

**Figure 3-6** Sequence diagram for the printer, the blanks supplier, and the raw material supplier companies.

In the following sections, the formation of the implementation model in ARENA simulation language is presented.

## 3.7 The implementation model

In this section the design and development of an implementation model based on the conceptual model associated with ARENA simulation language is presented.

The implementation model of the supply chain in the ARENA simulation language was developed to have the following modelling features:

- Dynamic: the model progresses with time.
- Stochastic: modelling with random inputs.
- Discrete: the state of the system can change only at separated points in time.
- Process orientation: the system is represented by combining a flowchart of processes that system entities undergo with the data required to characterise the system completely.
- Concurrency: allowing simultaneous execution of more than one process.
- Event orientation: the recording of each event that could change the state of the system, tracking the pertinent characteristics of the system (statistical accumulators, event calendars, etc.) for use by the logic behind each subsequent event.

Although it is limited to these features, this is sufficient to accurately model the relevant aspects of the systems.

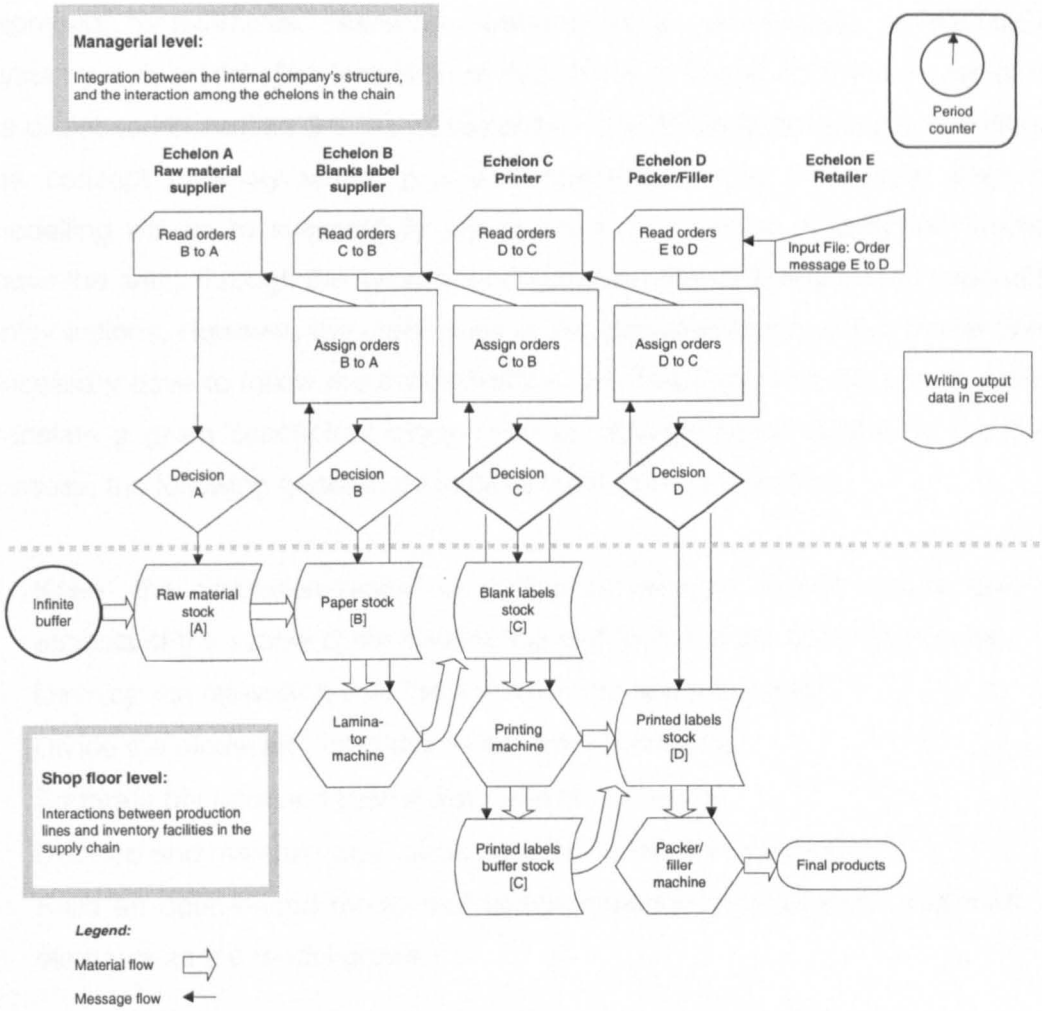



**Figure 3-7**. A process chart representation of the implementation model

A general coverage on how to carry out effective simulation modelling, analysis, and projects in ARENA environment can be found in [KeltSaSa 98]. Figure 3-7 shows the overall process chart representation for the implementation model that has been evolved during this investigation. The model is represented by a number of unique sub-models. These sub-models represent a central clock, an inventory facility, a production facility, the 'managerial unit' (logic decisions), an arrival of orders for materials, and a writing routine, as required in the complete model.

The basic building blocks for each sub-model consists of modules designed to represent, for examples, resources, systems entities, and delays, as required in the system's sub-model. The formation of this model is based on the conceptual model as discussed in section 3.5. As stated above, the ARENA modelling orientation uses the concept of entity-based, process orientation. Thus, the crucial step in the modelling will be to successfully laying out the sequence of activities required to move the entity through the system, and supplying the data required to support these entity actions. However, the chronology of the implementation of this model does not necessary have to follow the conceptual model. The important issue is to accurately translate a given conceptual model into an implementation model. In the building process, the following general procedures have been undertaken.

- Keep the simulation model as simple as possible and to include only those aspects of the supply chain system that is relevant to the study objectives
- Develop the relevant model input procedures and interfaces.
- Divide the model into relatively small logical elements.
- Separate physical and logical elements of the model.
- Develop and maintain clear documentation directly in the model.
- Build an open-ended model that allows insertion of extensions and more detail elements as the model grows.

The following describes the important features of the model:

### 3.7.1 The general system's requirements

This simulation model can be understood as a numerical model, consisting of templates that can be uniquely assigned by variable names, that represent the resources, queues, storages, and etc., and is linked together by some relevant mathematical relationships. Throughout the simulation runs, several tasks have to be accomplished. The tasks include the recording, processing, and computing the data (variables) containing information on every event and state of the system. These variables explicitly represent the model's system dynamics. In most instances, the model requires that the happening of a subsequent event is related to the occurrence of another event or several other events. Hence, it is vital that the timing of the

system's sub-models be effectively synchronised. To accomplish this, a central time reference is modelled to ensure that the events and activities are referred to a single standard time reference.

The sub-model *Period Counter* is built to provide the necessary central time reference to synchronise the timing of the model. The smallest unit used is defined as one hour, and 24 hours to make up one day, and followed by seven days to make up one week, and subsequently four weeks to become one month.

For simplicity, it is assumed that there will be an infinite supply of raw materials to the first echelon. For this purpose, the sub-model *Infinite Buffer* is modelled to supply sufficient raw materials to the *Raw Material Stock [A]*.

### 3.7.2 The interactions of information

This section presents the approach used in this work for the modelling of the placement and the transmission of ordering information upstream, while simultaneously tracking and controlling the flow of system entities down the echelons through the facilities (production and inventory sites). Each facility will be modelled as a sub-model and has to be 'reactive' (event-driven) to: (a) the flow of orders information, and (b) the flow of system entities.

Basically, data representing the flow of ordering information between the echelons is assigned as global variables, that is in a format accessible by the other partners in the chain. As time progresses, each variable representing one component of the orders (messages) will be fetched (read), processed and executed, appropriately. Each time, on the occurrence of a new event this variable will be written or replaced with a new value.

As an illustration, a message/order information is assigned and utilised in the model as follows:

- At 07.00 hours a message is passed from echelon E (the retailer) to echelon D. One component of this message is the order quantity.

- The order quantity is assigned as a variable ($u_E(d)$) and is made accessible to the next immediate echelon (D) within a time range: In this case between 07.00 hours and 08.00 hours.
- This value will be read as the order quantity from retailer to packer/filler.
- At 08.00 hours this value will be assigned to represent the required quantity to be produced in the production facility (packer/filler).
- This variable ($u_E(d)$) will be assigned with a new value when a new message arrives on the next day.

#### 3.7.2.1 Modelling the flow of messages

The following sub-sections provide the implementation of the approach in modelling the upstream flow of orders information. The first sub-model was modelled to read data from an input file. The second, third and fourth sub-models were modelled to allow data representing the order quantity to be generated and later to be deployed by its immediate upstream echelon. A detailed implementation model is described in the section on model verification.

- **First sub-model: Echelon E to echelon D message flows**

The orders from retailer is read from a data file. For simplicity this information is written in a text file. The data file representing orders is defined as an array of ***r*** rows (***r*** equals to the number of days), and two columns. For example, each row corresponds to each day of operation and each of the two columns corresponds to the ordering date, and the quantity to order, respectively. The arrival of order is scheduled at 07.00 hours everyday and it is assumed to be at the same time for the rest of the simulation days. The reading of the data file is repeated until the end of the simulation: specified to be *d* days in the SIMULATE block, where *d* is an integer value representing the number of days to be simulated.

- **Second sub-model: Echelon D to echelon C message flows**

This is assigned based on the ordering policy for echelon D. The decision is to place a usual weekly order of $Q_D = 7^* u_{Ess} = 700$ units every Sunday (day, *i*.eq.0).
On any other day if the printed label stock in echelon D , plus the quantity on order not yet delivered, falls to or below a threshold value, $s_{Dthreshold}$ , i.e.,

$$l_D(d) + \sum_{i=0}^{d} [y_C(i) - u_D(i)] \leq s_{D\,threshold}$$

the decision is to place an order of printed labels equal to , $e = 7^* u_E(w+i) - I_D(7w+i)$ *to replenish the stock.*

In addition to the blank labels stock, there is also a buffer stock of printed labels in company C to hold a stock of printed labels. The quantity is typically between 100 and 200 units. The inventory policy is that sufficient labels are held in stock to meet needs 1qa\of a sudden increase in order from packer/filler.

The blank label stock will be in rolls of fixed size and will be able to produce a set number of printed labels. The decisions about operation for modelling purposes have to consider whether to print *p* units and take 100 units from the buffer stock, or to print *q* units and add 100 units to stock.

The control decision is as follows:
*If buffer stock.le.100 units, print* $p_C(d)=y_D(d)+100$ *units and add 100 units to buffer stock.*
*If buffer stock.ge. 200 units, print* $p_C(d)=y_D(d)-100$ *units and take 100 units from buffer stock.*

- **Third sub-model: Echelon C to echelon B message flows**

This is assigned based on the amount of blank labels left in the blank label stock in echelon C. The policy is to place a usual weekly order of $Q_C$=2450 units if the

inventory level drops below $s_C$, where $S_C$=4900 and $s_C$=2450. Otherwise no orders will be placed.

*If stock + quantity on order .le. $s_C$, the order = $Q_C$*

- **Fourth sub-model: Echelon B to echelon A message flows**

This is assigned based on the amount of paper and materials that remain in the paper stock in echelon B. The policy is to place a usual order of $Q_B$ = 8600 units if the inventory level drops below 8600. $S_B$=17200 and $s_B$=8600. Otherwise no orders will be placed.

*If stock + quantity on order .le. $s_B$, the order = $S_B$-$s_B$= $Q_B$*

### 3.7.3 The tracking and controlling of systems entities

The next key issue is how to model the tracking and controlling the flow of system entities (materials). This section presents the methodology used for modelling this requirement.

It is assumed that the entities originate from the raw material supplier A, and are available at all times. As the entities flow through the system, they will be processed by a series of resources. Resources are anything the entities need to be processed for example, machine (production facility) and storage space (inventory). These entities arrive, and join queues to wait the assignment of required resources, and then processed by the resources, later to be released and finally exit the system. To co-ordinate the operation of these events, logical and mathematical relationships were introduced parsimoniously into the model. Together with the facilities sub-models (production, inventory), and the sub-models for message flows, these relationships (defined as variables) form the interlinking of dependent variables that changes states with the changes of events.

Of special interest to this research is also that, the model has to keep track of the advances in time, as well as keeping track of production sizes, inventory level at a particular time of the day, and some other desired statistics.

The remaining steps taken in the modelling process, that is the verification, the validation, the experimental design, and the presentation of results will be covered in the succeeding chapters.

## 3.8 Summary

This chapter covers the work devoted to expand the research in simulation and modelling of a supply chain system. It sets out how the work should be approached and describes the key stages (modelling procedures) and the processes that interlink these stages, see Figure 3-1. It involves many activities from understanding the problem to be tackled, to building, testing and experimenting with the model, leading to analysis and interpretation of the results.

As a first step, a conceptual description of the model is constructed. A conceptual model lists the elements to be included in the model (the scope) and the detail required for each of those elements (the level of detail) including the relationships between them (the control rules and flow of entities). Sequence diagram is later used to represent the conceptual model. Once the conceptual model is sufficiently developed, it can be converted into a computer model (the implementation model). Finally, this chapter describes the design and development of an implementation model for a supply chain using discrete-event simulation (DES) ARENA. Methods proposed in this chapter offers some promising tools for building a model of high complexity like a supply chain.

In the following chapter, model verification and validation are performed to determine the correctness of the model operation. Verification seeks to show that the computer program performs as expected and intended, thus providing a correct logical representation of the model. Validation established that the model behaviour validly represents that of the real system being simulated. Both processes involve system testing that demonstrates different aspects of model accuracy.

# Chapter 4

# Model Verification and Validation

## 4.1 Introduction

The process of determining the correctness of model operation typically consists of two separate functions: verification and validation. Verification and validation activities are an on-going process throughout the modelling and simulation phases. A number of researchers including Caughlin, see [Caughlin 00] suggest that whilst verification seeks to show that the computer program performs as expected and intended, validation, on the other hand, establishes that the model behaviour validly represents that of the real-world system being simulated. Both processes involve system testing that demonstrates different aspects of model accuracy.

In another paper, Sargent [Sargent 00] summarises that *"model verification and validation are critical in the development of a simulation model. Unfortunately, there is no set of specific tests that can easily be applied to determine the 'correctness' of the model. Furthermore, no algorithm exists to determine what techniques or procedures to use. Every new simulation project presents a new and unique challenge"*.

This chapter concentrates on the verification and the validation processes conducted to show that the simulation model performs as expected and intended, and establishes that the model behaviour validly represents that of the system being simulated. As normally practised, first the verification process is conducted, and this is followed by the discussion on the validation process.

## 4.2 Model verification

Pegden *et. al* [PegdSS 95], described verification as "*the process of determining that a model operates as intended. Throughout the verification process, we try to find and remove unintentional errors in the logic of the model. This activity is commonly referred to as debugging the model.*" In another paper, Balci [Balci 98] regarded model verification as follows: *"Model verification is substantiating that the model is transformed into another, as intended, with sufficient accuracy. Model verification deals with building the model right".*

As noted by many researchers, see for example Pegden *et. al* [PegdSS 95], Balci [Balci 98] , Caughlin [Caughlin 00] and Sargent [Sargent 00], verification is a process by which the modeller tries to assure himself that the conceptual model is properly realised in the computer program. The accuracy of converting a model representation from a conceptual model form into an executable computer program is evaluated in model verification.

Some approaches to the verification problem can be found in Jagdev *et. al.* [JagdBJ 95]. One of the techniques suggested for use is *program tracing.* In this technique variable values and program flow is checked against what the programmer (modeller) expects. The programmer then should focus on analysing the program for errors. Similar technique is used in this work. This approach was chosen because ARENA debugging tools provide the necessary facilities to perform the verification on the model.

### 4.2.1 Program tracing for base model

As has been discussed in Chapter 3, a process flow chart is first developed to represent the details of the implementation model, as required in the modelling. This process flow chart is the result of the transformation of the details described in the conceptual model. Figure 4-1, shows a process chart used to guide in checking the program flows. Note that each block in the process chart is assigned with an identification number for better model tractability.

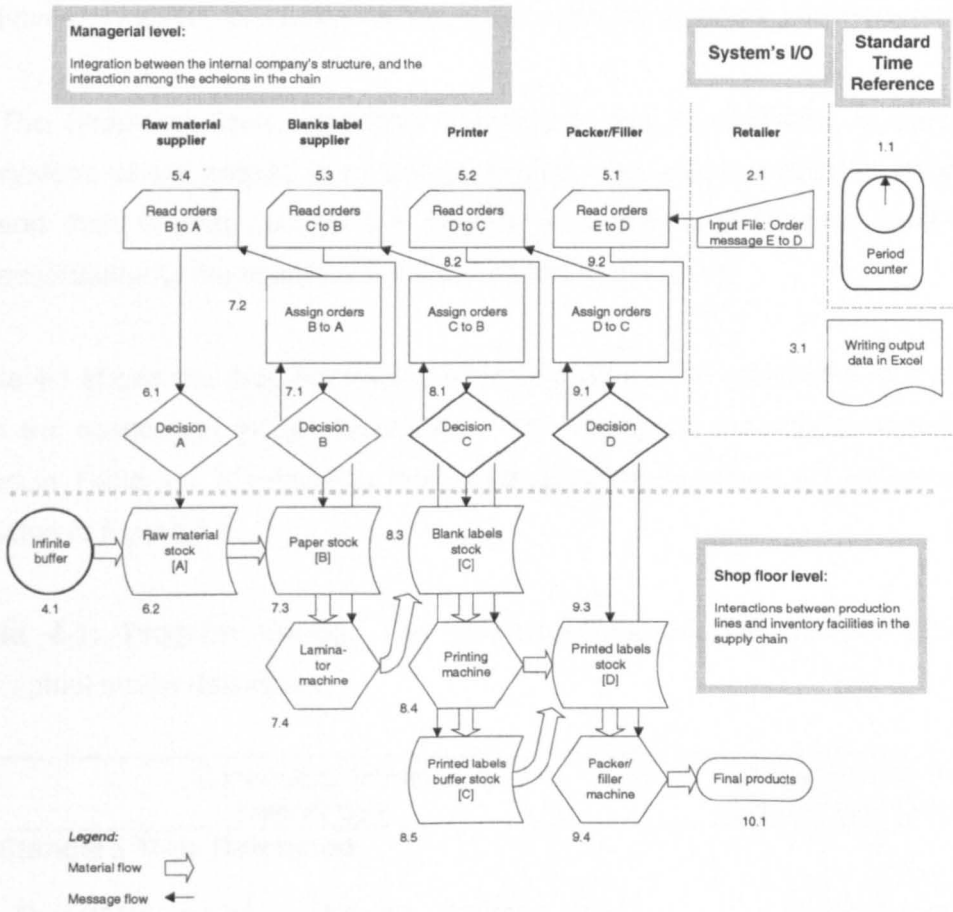



Figure 4-1. A process chart used in the verification process.

It describes in detail the four sections of the model, that is:

- *The Standard Time Reference*: a vital component in the model for the proper synchronisation of the timings for the events and activities.
- *The Managerial level* : modelling using variables that change values upon the changes of other variables representing 'managerial level' itself or in 'shop floor level'. The 'managerial unit', a sub-model in managerial level was modelled as rules representing the respective decision policy (inventory policy).

- *System's input and output*: a. facilitates the reading of data (stream of numbers) representing the orders from retailer, and b. facilitates the writing of output data (inventory levels, production sizes, order sizes) for analysis and interpretation.

- *The Shop-floor level*: modelling is similar to that of modelling a manufacturing system, where entities were first generated, and released from an infinite buffer, and then flowing through the various processes (productions, inventories) in accordance to the specified rules before being disposed.

Table 4-1 shows the program tracing steps to produce the sub-model representations from the conceptual model description. The conceptual sub-model representations noted in Table 4-1 is related to their corresponding blocks in the process chart as depicted in Figure 4-1.

**Table 4-1:** Program tracing: The sub-model representations as derived from conceptual model description

| Conceptual Model Description | Conceptual Model Sub-model Representation |
|---|---|
| **1. Standard Time Reference** | |
| The DEDS model is dynamic, therefore the passage of time plays a crucial role. A central time reference (clock) sub-model to enable events and activities be referred to a standard time reference is needed. This function is vital since the timing for all of the system's sub-models have to be effectively synchronised. | 1.1 Period Counter |
| **2 Mechanism to facilitate the coordination of entities flow.** ***The model section for 'Managerial level'*** | |
| Localised logic decision sub-model to manipulate the downstream information to control the upstream activities. This sub-model has the tasks of processing information (order quantity, inventory level, etc.) and generates specific instruction (in the form of a signal) to other sub-models (production site, inventory, etc.) to trigger (execute) the controlling of flow of system entities. This sub-model is a component of the 'managerial unit'. | 6.1 Decision A<br>7.1 Decision B<br>8.1 Decision C<br>9.1 Decision D |

| | |
|---|---|
| The managerial unit is modelled by having rules for how it will react to events, i.e., to model it as a sequence of rules (representing the order policy, or inventory policy). | |
| Routine to inform of when to access (read) an order message. | 5.1 Read orders E to D<br>5.2 Read orders D to C<br>5.3 Read orders C to B<br>5.4 Read orders B to A |
| Localised logic decision sub-model to generate the ordering messages. This message is generated with the proper correlation of the logical and mathematical relations of the available information from the facilities. This sub-model is a component of the 'managerial unit'. | |
| Routine to determine of when to assign (write) a new data (order information). The information is conveyed to the production facility at a regular interval. | 7.2 Assign orders B to A<br>8.2 Assign orders C to B<br>9.2 Assign orders D to C |
| To model the communication (information exchanges) between the echelons, initially the following assumptions will be made: the order (message) from echelon E to echelon D is being fedback daily, the order (message) from echelon D to echelon C will usually be delivered on a weekly basis, followed by normally a fort-nightly basis for the order (message) to be passed upstream from echelon C to echelon B, and for the most part on a monthly basis for a message to be delivered from echelon B to echelon A.<br><br>*Note:* During some point of the simulation work it has been found that the orders from C to B, and also from B to A have to be reviewed on a weekly basis. | |
| **3. Develop system's inputs and outputs explicitly.**<br>***The model section for System Input/Output*** | |
| Reading from an input file (for example, a text file) that will represent the order arrivals from the end customer. The orders (messages), as a means of communication between the echelons behaves as feedback signals. | 2.1 Input File: Order Message E to D |
| Writing output data (results) to an output file (for example, Excel) for graphical representation of the order/demand quantities, the inventory levels, and the production rates at a particular facility of interest over a period of time. These observations could then be analysed, and consequently the | 3.1 Writing output data in EXCEL |

| | |
|---|---|
| true system (supply chain model) performance measures can be estimated. The information gathered can be used to evaluate and redesign the supply chain parameters, for example the inventory policy. | |
| **4. Define the system's behaviour, explicitly.** ***The model section for Shop floor level*** | |
| Each echelon is represented by a number of sub-models. For example echelon C will be represented by its sub-models consisting of the production site, inventories, and a 'managerial unit', which can make active decisions. The later is 'reactive' to the order (message) and able to coordinate the flow of system entities (materials) through the processes.<br><br>The system entities for example the raw material, behave as the objects that change states (attributes) as they move through the production site and inventories. These systems entities will be processed and transformed into new products (ie., assigned with new attributes) as they are being directed downstream from one echelon to the next echelon. | **The production sub-models**:<br>7.4 Laminator machine<br>8.4 Printing machine<br>9.5 Packer/Filler machine<br><br>**The inventory sub-models**:<br>4.1 Infinite Buffer<br>6.2 Raw material stock<br>7.3 Paper stock<br>8.3 Blank label stock (Printer inventory)<br>8.5 Normal label stock in C (Printer buffer/intermediate inventory)<br>9.3 Normal label stock (Packer/filler inventory)<br>10.1 Echelon E Warehouse (Retailer) |

### 4.2.2 Programming implementation model on ARENA

The debugging process is performed accordingly, and the variables values and program flow is checked for errors. In tracking the details of the model, the sequence diagrams as has been discussed in Chapter 3, is referred to throughout the programming process. The references available in [Arena 95a], [Arena 95b], [Arena 95c], and [Arena 95d] are used to provide clarification on the technical jargons in the modelling language encountered during the programming.

This implementation model, a result of successful transformation and coding into ARENA language will be used as the 'Base model' for the supply chain that implements the generic policy at the packer/filer, the $(s,S)$ policy at the printer and also the $(s,S)$ policy at the blanks labels supplier. Note that the simulation model has a modular structure that allows the alteration of certain parameters in the model

(example inventory policy), without affecting the physical structure of the overall model.

## 4.3 Model validation

Law and Kelton [LawK 91], defined validation as follows: " *validation is concerned with determining whether the conceptual simulation model (as opposed to the computer program) is an accurate representation of the system under study".* Kleijnen [Kleijnen 95a] pointed out that "*validation cannot result in a perfect model: the perfect model would be the real system itself. Instead, the model should be 'good enough', which depends on the goals of the model* ". In another article, Balci [Balci 97] described validation as building the right model. He pointed out that model validation substantiates that the model behaves with sufficient accuracy in light of the study's objectives.

There is an abundance of literature on model validation advocating the diverse techniques. These techniques include:

- conceptual model validation: the aim is to determine whether the scope and level of detail of the proposed model is sufficient for the purpose at hand, and that any assumptions are correct.
- white-box validation: the aim is to determine whether the constituent parts of the computer model represent the corresponding real world elements with sufficient accuracy. This is a detailed, or micro, check of the model.
- black-box validation: the aim is to determine whether the overall computer model represents the real world with sufficient accuracy. This is an overall, or macro, check of the model's operation.
- dynamic validation technique: a functional testing conducted to assess the accuracy of the model based upon its output, given a specific sets of inputs.
- static validation technique: traceability assessment conducted to assess the accuracy of a model based upon characteristics of the static simulation model design and source code.

More detailed discussions can be found in Sargent [Sargent 00], Balci [Balci 97], Kleijnen [Kleijnen 95b], Robinson [Robinson 97], Brooks and Robinson [BrooksR 01], and Swisher, Jacobson, Jun and Balci [SwJJB 01].

Brooks and Robinson [ BrooksR 01] pointed out that it is not possible ever to say that a model is valid, because it is not possible to test every aspect of a model. In particular, problems exist because:

- There are insufficient accurate real world data for comparison purposes;
- Most simulations are models of proposed system (that is, a change to an existing system or a completely new system), not currently existing ones, making comparison impossible;
- There is simply insufficient time to verify and validate all aspects of a model.

### 4.3.1 Model validation: Comparisons of simulation results to calculations of systems equations.

In the validation process, the approach suggested by Law and Kelton was adopted. They stated that " *the state of the simulated sub-system was printed out and compared with manual calculation to see if the program was operating as intended*", [LawK 91].

The validation has been conducted by comparing the simulation results to the results from calculation of the mathematical relationships from the basic system equations. The purpose is to be able to know whether the simulation model represents the system as described in the problem definition with sufficient accuracy. This approach was chosen because even though the real data is not available:

- the basic systems' equations can be derived and input data can be generated.
- many aspects of the model can be validated, including the timings, the control of the elements, the control of flows, and the control logic, by a. checking the codes, b. inspection of results, and c. visual inspections of the outputs.

As mentioned earlier, the key reasons for performing this simulation study is to determine the probable performance of the system, where several 'what if' scenarios can be conducted. The fact that the simulation model has been developed based on a typical FMCG supply chain has made it difficult for the modeller to validate it because real data are not available. The simulation model in all aspects is a computer model that has close resemblance to the FMCG, as described in the problem definition. In view of these situations, therefore, the simulation model can be regarded as a change to the existing system or a completely new system, not currently existing ones, since making comparison to the real system is impossible (in these cases because real data are not available).

The validation has been conducted as follows:

- The work is performed to validate that the results from simulation, or more precisely the data being read at 9 am in the simulation model is consistent with the values from calculations.

- The calculations using the defined variables required to produce output data for Base model, with d=7 to 22, are shown in Table 4-1. Suppose that the orders from retailer has the following pattern: 100 units per day, from day 1 to day 8 followed by 150 units per day from day 9 to day 15, and then reduces to 100 units per day from day 16 onwards.

A segment of the output from simulation is shown as an insert in Table 4-1. The derivation of the basic system equations and the detailed calculations involved are as follows:

Define,

$u_E(d)$, the retailer's order on day $d$

$y_D(d)$, Goods delivered by packer/filler on day $d$

$p_D(d)$, the production at packer/filler on day $d$.

$I_D(d)$, Packer/filler's inventory on day $d$

$u_D(d)$, the Packer/filler's order on day $d$

$y_C(d)$, Goods delivered by printer on day $d$.

$p_C(d)$, the production at printer on day $d$.

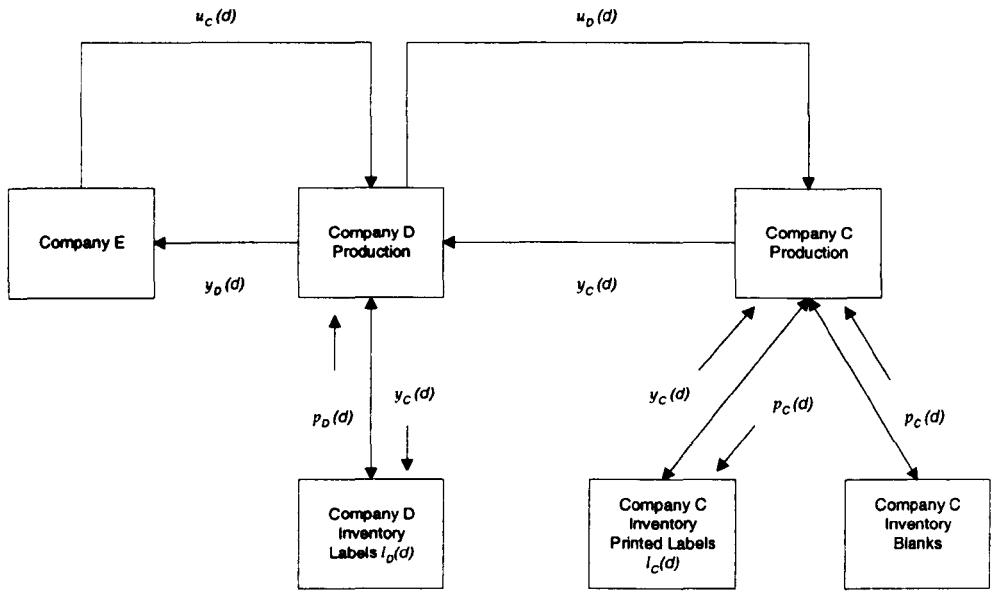



**Figure 4-2** Schematic diagram for the basic system equations

Figure 4-2 gives a schematic diagram for the supply chain system and is used for deriving the basic system equations. As shown, it is convenient for this purpose to represent the system as consisting of the retailer (company E), the packer/filler (company D) and the printer (company C). The basic system equations are derived using the notation of Figure 4-2.

The equations are as follows:

$$y_C(d) = \begin{cases} u_D(d-3), & l_C(d) \geq u_D(d-3) \\ l_C(d), & l_C(d) < u_D(d-3) \end{cases} \qquad (4.1)$$

$$p_D(d) = \begin{cases} u_E(d), & l_D(d) \geq u_E(d) \\ l_D(d), & l_D(d) < u_E(d) \end{cases} \quad (4.2)$$

$$y_D(d) = p_D(d-1)$$

$$l_D(d+1) = l_D(d) - y_D(d) + y_C(d) \quad (4.3)$$

$$l_C(d+1) = l_C(d) - y_C(d) + p_C(d-1) + p_C(d-2) + p_C(d-3) \quad (4.4)$$

The following calculations were performed to demonstrate that the results from calculations agreed with the output from simulation.

*Sample simulation input*:

A pulse input, $u_E(d)$ is applied from $d$=9 to $d$=15, that is, assuming the retailer has the following ordering pattern: 100 units per day, from day 1 to day 8 followed by 150 units per day from day 9 to day 15, and then reduces to 100 units per day from day 16 onwards.

The tabulation of sample calculations for simulation on the Base model, with d=7 to 22, for the supply chain system as shown in Figure 4-2, are shown in Table 4-2.

The detailed calculations involved are as follows:

Day $d$=7: the retailer's order ,$u_E(d)$, as issued at 7 am is 100 units. At 8.15 am, 100 units of printed labels are sent for production, and as a result the packer/filler's inventory, $l_D(d)$, is reduced by 100 units. As shown at 9 am, its value is calculated to be 800-100=700 units. At 10 pm, the goods delivered by packer/filler, $y_D(d)$, is 100 units (as indicated by the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 100, 100, 700, 0* and *0*, respectively.

Day $d$=8: the retailer's order ,$u_E(d)$, as issued at 7 am is 100 units. At 8.15 am, 100 units of printed labels are sent for production. As shown at 9 am, the packer/filler's inventory , $l_D(d)$, is calculated to be 700-100=600 units. An hour earlier, the packer/filler issued an order, $u_D(d)$, of 700 units. As shown at 10 pm, 100 units of goods produced by packer/filler is delivered to retailer ($y_D(d)$ = 100) (as indicated by

the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 100, 100, 600, 700* and *0*, respectively.

Day $d$=9 : the retailer's order ,$u_E(d)$, as issued at 7 am is 150 units. At 8.15 am, 150 units of printed labels are sent for production. As shown at 9 am, the packer/filler's inventory , $l_D(d)$, is calculated to be 600-150=450 units. The production of printed labels (700 units) as ordered by the packer/filler on the previous day is completed at 2 pm (as indicated by the dashed arrow). This quantity is to be delivered before 5 pm, on the third day after the order was issued: the quantity is expected to be delivered on day, $d$=(8+3) =11 by 5 pm. As shown at 10 pm (as indicated by the arrow), 150 units of goods produced by packer/filler is delivered to retailer, ($y_D(d)$ = 150). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 150, 100, 450, 0* and *0*, respectively.

Day $d$=10: the retailer's order, $u_E(d)$, as issued at 7 am is 150 units. At 8.15 am,150 units of printed labels are sent for production, and as a result the packer/filler's inventory , $l_D(d)$, is reduced by 150 units. As shown at 9 am, its value is calculated to be 450-150=300 units. The printer's production, $y_C(d)$ is read as 700 units. At 10 pm, the goods delivered by packer/filler, $y_D(d)$, is calculated to be 150 units (as indicated by the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 150, 150, 300, 0* and *700*, respectively.

Day $d$=11: the retailer's order, $u_E(d)$, as issued at 7 am is 150 units. At 8.15 am, 150 units of printed labels are sent for production. As shown at 9 am, the packer/filler's inventory, $l_D(d)$, is calculated to be 300-150=150 units. The printed labels as ordered by the packer/filler on day $d$=8 is received at 5 pm (as indicated by the dashed arrow). These quantities are added to the current packer/filler's inventory, and this is calculated equals to 700+150=850 units. At 10 pm (as indicated by the arrow), 150 units of goods produced by packer/filler is delivered to retailer ( $y_D(d)$ = 150). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$*at 9 am are 150, 150, 150, 0* and *0*, respectively.

Day $d$=12: the retailer's order, $u_E(d)$, as issued at 7 am is 150 units. At 8.15 am, 150 units of printed labels are sent for production, and as a result the packer/filler's

inventory , $l_D(d)$, is reduced by 150 units. As shown at 9 am, its value is calculated to be 850-150=700 units. At 10 pm, the goods delivered by packer/filler, $y_D(d)$, is calculated to be 150 units (as indicated by the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 150, 150, 700, 0* and *0*, respectively.

Day $d$=13: the retailer's order, $u_E(d)$, as issued at 7 am is 150 units. At 8.15 am, 150 units of printed labels are sent for production, and as a result the packer/filler's inventory , $l_D(d)$, is reduced by 150 units. As shown at 9 am, its value is calculated to be 700-150=550 units. At 10 pm, the goods delivered by packer/filler, $y_D(d)$, is calculated to be 150 units (as indicated by the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d$ *at 9 am are 150, 150, 550, 0* and *0*, respectively.

Day $d$=14: the retailer's order, $u_E(d)$, as issued at 7 am is 150 units. At 8.15 am,150 units of printed labels are sent for production, and as a result the packer/filler's inventory , $l_D(d)$, is reduced by 150 units. As shown at 9 am, its value is calculated to be 550-150=400 units. At 10 pm, the goods delivered by packer/filler, $y_D(d)$, is calculated to be 150 units (as indicated by the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 150, 150, 400, 0* and *0*, respectively.

Day $d$=15: the retailer's order, $u_E(d)$, as issued at 7 am is 150 units. At 8.15 am, 150 units of printed labels are sent for production. As shown at 9 am, the packer/filler's inventory, $l_D(d)$, is calculated to be 400-150=250 units. An hour earlier, the packer/filler issued an order, $u_D(d)$ of 700 units. At 10 pm (as indicated by the arrow), 150 units of goods produced by packer/filler is delivered to retailer ( $y_D(d)$ = 150). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$*at 9 am are 150, 150, 250, 700* and *0*, respectively.

Day $d$=16: the retailer's order, $u_E(d)$, as issued at 7 am is 100 units. At 8.15 am, 100 units of printed labels are sent for production, and as a result the packer/filler's inventory, $l_D(d)$, is reduced by 100 units. As shown at 9 am, its value is calculated to be 250-100=150 units. The production of printed labels, 700 units, as ordered by the

packer/filler on the previous day is completed by 2 pm (as indicated by the dashed arrow). This quantity is to be delivered before 5 pm, on the third day after the order was issued, that is the quantity is expected to be delivered on day, $d$=(15+3)=18. At 10 pm, the goods delivered by packer/filler, $y_D(d)$, is calculated to be 150 units (as indicated by the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 100, 150, 150, 0* and *0*, respectively.

Day $d$=17: the retailer's order, $u_E(d)$, as issued at 7 am is 100 units. At 8.15 am,100 units of printed labels are sent for production, and as a result the packer/filler's inventory , $l_D(d)$, is reduced by 100 units. As shown at 9 am, its value is calculated to be 150-100=50 units. The printer's production, $y_C(d)$ is read as 700 units. At 10 pm, the goods delivered by packer/filler, $y_D(d)$, is calculated to be 100 units (as indicated by the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 100, 100, 50, 0* and *700*, respectively.

Day $d$=18: the retailer's order, $u_E(d)$, as issued at 7 am is 100 units. At 8.15 am, only 50 units of printed labels are sent for production, and as the packer/filler's inventory , $l_D(d)$, has only 50 units left. As shown at 9 am, its value is calculated to be 50-50=0 units. A decision is made to place an emergency order, $e = 7 * u_E(d) - l_D(d) = 650$ , after $l_D(d)$ + quantity on order, drops below $s_{D\ \mathrm{threshold}}$. The printed labels as ordered by the packer/filler on day $d$=15 is received at 5 pm (as indicated by the dashed arrow). These quantities are added to the current packer/filler's inventory, and this equals to 0+700=700 units. At 10 pm, the goods delivered by packer/filler, $y_D(d)$, is calculated to be 50 units (as indicated by the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 100, 100, 0, 650* and *0*, respectively.

Day $d$=19: the retailer's order, $u_E(d)$, as issued at 7 am is 100 units. At 8.15 am, 100 units of printed labels are sent for production, and as a result the packer/filler's inventory , $l_D(d)$, is reduced by 100 units. As shown at 9 am, its value is calculated to be 700-100=600 units. The production of printed labels, 650 units, as ordered by the packer/filler on the previous day is completed by 2 pm (as indicated by the dashed arrow). This quantity is to be delivered before 5 pm, on the third day after the order

was issued, that is the quantity is expected to be delivered on day, $d$=(18+3)=21. At 10 pm, the goods delivered by packer/filler, $y_D(d)$, is calculated to be 100 units (as indicated by the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 100, 50, 600, 0* and *0*, respectively.

Day $d$=20: the retailer's order, $u_E(d)$, as issued at 7 am is 100 units. At 8.15 am,100 units of printed labels are sent for production, and as a result the packer/filler's inventory , $l_D(d)$, is reduced by 100 units. As shown at 9 am, its value is calculated to be 600-100=500 units. . The printer's production, $y_C(d)$ is read as 650 units. At 10 pm, the goods delivered by packer/filler, $y_D(d)$, is calculated to be 100 units (as indicated by the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 100, 100, 500, 0* and *650*, respectively.

Day $d$=21: the retailer's order, $u_E(d)$, as issued at 7 am is 100 units. At 8.15 am,100 units of printed labels are sent for production, and as a result the packer/filler's inventory , $l_D(d)$, is reduced by 100 units. As shown at 9 am, its value is calculated to be 500-100=400 units. The printed labels as ordered by the packer/filler on day $d$=18 is received at 5 pm (as indicated by the dashed arrow). These quantities are added to the current packer/filler's inventory, and this equals to 400+650=1050 units. At 10 pm, the goods delivered by packer/filler, $y_D(d)$, is calculated to be 100 units (as indicated by the arrow). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$ *at 9 am are 100, 100, 400, 0* and *0*, respectively.

Day $d$=22: the retailer's order, $u_E(d)$, as issued at 7 am is 100 units. At 8.15 am, 100 units of printed labels are sent for production. As shown at 9 am, the packer/filler's inventory, $l_D(d)$, is calculated to be 1050-100=950 units. An hour earlier, the packer/filler issued an order, $u_D(d)$ of 700 units. At 10 pm (as indicated by the arrow), 100 units of goods produced by packer/filler is delivered to retailer ( $y_D(d)$ = 100). The simulation results show that the values for $u_E(d)$, $y_D(d-1)$, $l_D(d)$, $u_D(d)$, and $y_C(d)$*at 9 am are 100, 100, 950, 700* and *0*, respectively.

**Table 4-2** Tabulation of sample calculations for data validation as produced in simulation for Base model, $d$=7 to 22.

| | | d=7 | | | | d=8 | | | | d=9 | | | | d=10 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 8am | 9am | 2pm | 10pm | 8am | 9am | 2pm | 10pm | 8am | 9am | 2pm | 10pm | 8am | 9am | 2pm | 10pm |
| 1 | $u_E(d)$ | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| 2 | $y_D(d)$ | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 150 | 150 | 150 | 150 | 150 |
| 3 | $I_D(d)$ | 800 | 700 | 700 | 700 | 700 | 600 | 600 | 600 | 600 | 450 | 450 | 450 | 450 | 300 | 300 | 300 |
| 4 | $u_D(d)$ | 0 | 0 | 0 | 0 | 700 | 700 | 700 | 700 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | $y_C(d)$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 700 | 700 | 700 | 700 | 0 | 0 |

| | | d=11 | | | | d=12 | | | | d=13 | | | | d=14 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 8am | 9am | 5pm | 10pm | 8am | 9am | 2pm | 10pm | 8am | 9am | 2pm | 10pm | 8am | 9am | 5pm | 10pm |
| 1 | $u_E(d)$ | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| 2 | $y_D(d)$ | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| 3 | $I_D(d)$ | 300 | 150 | 850 | 850 | 850 | 700 | 700 | 700 | 700 | 550 | 550 | 550 | 550 | 400 | 400 | 400 |
| 4 | $u_D(d)$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | $y_C(d)$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | d=15 | | | | d=16 | | | | d=17 | | | | d=18 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 8am | 9am | 2pm | 10pm | 8am | 9am | 2pm | 10pm | 8am | 9am | 2pm | 10pm | 8am | 9am | 5pm | 10pm |
| 1 | $u_E(d)$ | 150 | 150 | 150 | 150 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 2 | $y_D(d)$ | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 50 |
| 3 | $I_D(d)$ | 400 | 250 | 250 | 250 | 250 | 150 | 150 | 150 | 150 | 50 | 50 | 50 | 50 | 0 | 700 | 700 |
| 4 | $u_D(d)$ | 700 | 700 | 700 | 700 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 650 | 650 | 650 | 650 |
| 5 | $y_C(d)$ | 0 | 0 | 0 | 0 | 0 | 0 | 700 | 700 | 700 | 700 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | d=19 | | | | d=20 | | | | d=21 | | | | d=22 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 8am | 9am | 2pm | 10pm | 8am | 9am | 2pm | 10pm | 8am | 9am | 5pm | 10pm | 8am | 9am | 5pm | 10pm |
| 1 | $u_E(d)$ | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 2 | $y_D(d)$ | 50 | 50 | 50 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 3 | $I_D(d)$ | 700 | 600 | 600 | 600 | 600 | 500 | 500 | 500 | 500 | 400 | 1050 | 1050 | 1050 | 950 | 950 | 950 |
| 4 | $u_D(d)$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 700 | 700 | 700 | 700 |
| 5 | $y_C(d)$ | 0 | 0 | 650 | 650 | 650 | 650 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| $d$ | $u_E(d)$ | $y_D(d)$ | $I_D(d)$ | $u_D(d)$ | $y_C(d)$ |
|---|---|---|---|---|---|
| 1 | 100 | 100 | 600 | 700 | 0 |
| 2 | 100 | 100 | 500 | 0 | 0 |
| 3 | 100 | 100 | 400 | 0 | 700 |
| 4 | 100 | 100 | 300 | 0 | 0 |
| 5 | 100 | 100 | 900 | 0 | 0 |
| 6 | 100 | 100 | 800 | 0 | 0 |
| 7 | 100 | 100 | 700 | 0 | 0 |
| 8 | 100 | 100 | 600 | 700 | 0 |
| 9 | 150 | 100 | 450 | 0 | 0 |
| 10 | 150 | 150 | 300 | 0 | 700 |
| 11 | 150 | 150 | 150 | 0 | 0 |
| 12 | 150 | 150 | 700 | 0 | 0 |
| 13 | 150 | 150 | 550 | 0 | 0 |
| 14 | 150 | 150 | 400 | 0 | 0 |
| 15 | 150 | 150 | 250 | 700 | 0 |
| 16 | 100 | 150 | 150 | 0 | 0 |
| 17 | 100 | 100 | 50 | 0 | 700 |
| 18 | 100 | 100 | 0 | 650 | 0 |
| 19 | 100 | 50 | 600 | 0 | 0 |
| 20 | 100 | 100 | 500 | 0 | 650 |
| 21 | 100 | 100 | 400 | 0 | 0 |
| 22 | 100 | 100 | 950 | 700 | 0 |
| 23 | 100 | 100 | 850 | 0 | 0 |
| 24 | 100 | 100 | 750 | 0 | 700 |

**Data is recorded at 0900 hrs, on day, $d$**

*Note*: $y_D(d)^*$ represents $y_D(d-1)$, since the actual $y_D(d)$ is delivered only at 2200 hrs. The data appeared at 0900 hrs is $y_D(d-1)$.

## 4.4 Simulation example

- **Simulation run for base model**

The purpose of this simulation is to observe the behaviour of the system ( at the productions and inventories), subjected to a certain pattern of retailer's orders.

The decision policy implemented at companies D the packer/filler, C the label printer, and B the blanks producer respectively are as follows:

o *Decision policy at company D:*

*If day is Sunday (i.eq.0), order a fixed quantity of Q=700 units.* [Periodic review]
On any other day if the printed label stock in echelon D, plus the quantity on order not yet delivered, falls to or below a threshold value, $s_{Dthreshold}$ i.e.,

$$l_D(d) + \sum_{i=0}^{d}[y_C(i) - u_D(i)] \leq s_{D\,threshold}$$

the decision is to place an order of printed labels equal to , $e = 7^* u_E(w+i) - l_D(7w+i)$ *to replenish the stock.*

o *Decision policy at company C:*

Company C replenishes its stock using an order-up-to-production policy denoted by a heuristic (*s,S*) policy, where,
*S*, the order-up-to-level = 4900, and *s*, the re-order point = 2450.
*If stock + quantity on order .le. s, then order = S-s.*

In addition to the blank labels stock, there is also a buffer stock of printed labels in company C to hold a stock of printed labels. The quantity is typically between 100 and 200 units. The inventory policy is that sufficient labels are held in stock to meet needs of a sudden increase in order from packer/filler.

The blank label stock will be in rolls of fixed size and will be able to produce a set number of printed labels. The decisions about operations have to consider whether to print *p* units and take 100 units from the buffer stock, or to print *q* units and add 100 units to stock.

The control decision is as follows:

If buffer stock.le.100 units, print $p_C(d)=y_D(d)+100$ units and add 100 units to buffer stock.

If buffer stock.ge. 200 units, print $p_C(d)=y_D(d)-100$ units and take 100 units from buffer stock.

o *Decision policy at company B:*

Company B replenishes its stock using an order-up-to-production policy denoted by a heuristic (*s,S*) policy,

where, *S*, the order-up-to-level = 17200, and *s*, the re-order point = 8600.

*If stock + quantity on order .le. s, then order = S-s.*

- **Example:**

Suppose that the orders from retailer has the following pattern: 100 units per day, from day 1 to day 8 followed by 150 units per day from day 9 onwards, equivalent of a step pattern.

Table 4-3 shows the productions and inventory records at each company, from day *d* = 1 , until day, *d* = 60.

**Table 4-3** Ordering, production, and inventory records at each company, from day 1 to day 60.

| $d$ | $u_E(d)$ | $y_D(d-1)$ | $l_D(d)$ | $u_D(d)$ | $y_C(d)$ | $q$ | $p$ | $l_{C\,buffer}(d)$ | $l_C(d)$ | $u_C(d)$ | $yB(d)$ | $l_B(d)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 0 | 600 | 700 | 0 | 0 | 0 | 200 | 1050 | 0 | 0 | 11200 |
| 2 | 100 | 100 | 500 | 0 | 0 | 0 | 0 | 200 | 1050 | 0 | 0 | 11200 |
| 3 | 100 | 100 | 400 | 0 | 700 | 0 | 0 | 200 | 3500 | 0 | 0 | 11200 |
| 4 | 100 | 100 | 300 | 0 | 0 | 0 | 0 | 200 | 3500 | 0 | 0 | 11200 |
| 5 | 100 | 100 | 900 | 0 | 0 | 0 | 0 | 200 | 3500 | 0 | 0 | 11200 |
| 6 | 100 | 100 | 800 | 0 | 0 | 0 | 0 | 200 | 3500 | 0 | 0 | 11200 |
| 7 | 100 | 100 | 700 | 0 | 0 | 0 | 0 | 200 | 3500 | 0 | 0 | 11200 |
| 8 | 100 | 100 | 600 | 700 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 11200 |
| 9 | 150 | 100 | 450 | 0 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 11200 |
| 10 | 150 | 150 | 300 | 0 | 700 | 0 | 0 | 200 | 2800 | 0 | 0 | 11200 |
| 11 | 150 | 150 | 150 | 0 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 11200 |
| 12 | 150 | 150 | 700 | 0 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 11200 |
| 13 | 150 | 150 | 550 | 0 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 11200 |
| 14 | 150 | 150 | 400 | 0 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 11200 |
| 15 | 150 | 150 | 250 | 700 | 0 | 0 | 0 | 200 | 2100 | 0 | 0 | 11200 |
| 16 | 150 | 150 | 100 | 0 | 0 | 0 | 0 | 200 | 2100 | 0 | 0 | 11200 |
| 17 | 150 | 150 | 0 | 0 | 700 | 0 | 0 | 200 | 2100 | 0 | 0 | 11200 |
| 18 | 150 | 100 | 0 | 1050 | 0 | 0 | 0 | 200 | 1150 | 0 | 0 | 11200 |
| 19 | 150 | 0 | 550 | 0 | 0 | 0 | 0 | 200 | 1150 | 0 | 0 | 11200 |
| 20 | 150 | 150 | 400 | 0 | 800 | 0 | 0 | 200 | 1150 | 2450 | 0 | 11200 |
| 21 | 150 | 150 | 250 | 0 | 150 | 0 | 0 | 200 | 1150 | 0 | 0 | 8750 |
| 22 | 150 | 150 | 1150 | 700 | 0 | 0 | 100 | 100 | 350 | 0 | 2450 | 8750 |
| 23 | 150 | 150 | 1000 | 0 | 0 | 0 | 0 | 100 | 350 | 0 | 0 | 8750 |
| 24 | 150 | 150 | 850 | 0 | 800 | 0 | 0 | 100 | 2800 | 0 | 0 | 8750 |
| 25 | 150 | 150 | 700 | 0 | 0 | 100 | 0 | 200 | 2800 | 0 | 0 | 8750 |
| 26 | 150 | 150 | 1250 | 0 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 8750 |
| 27 | 150 | 150 | 1100 | 0 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 8750 |
| 28 | 150 | 150 | 950 | 0 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 8750 |
| 29 | 150 | 150 | 800 | 700 | 0 | 0 | 0 | 200 | 2100 | 0 | 0 | 8750 |
| 30 | 150 | 150 | 650 | 0 | 0 | 0 | 0 | 200 | 2100 | 0 | 0 | 8750 |
| 31 | 150 | 150 | 500 | 0 | 700 | 0 | 0 | 200 | 2100 | 0 | 0 | 8750 |
| 32 | 150 | 150 | 350 | 0 | 0 | 0 | 0 | 200 | 2100 | 0 | 0 | 8750 |
| 33 | 150 | 150 | 900 | 0 | 0 | 0 | 0 | 200 | 2100 | 0 | 0 | 8750 |
| 34 | 150 | 150 | 750 | 0 | 0 | 0 | 0 | 200 | 2100 | 2450 | 0 | 8750 |
| 35 | 150 | 150 | 600 | 0 | 0 | 0 | 0 | 200 | 2100 | 0 | 0 | 6300 |
| 36 | 150 | 150 | 450 | 700 | 0 | 0 | 0 | 200 | 1400 | 0 | 2450 | 6300 |
| 37 | 150 | 150 | 300 | 0 | 0 | 0 | 0 | 200 | 1400 | 0 | 0 | 6300 |
| 38 | 150 | 150 | 150 | 0 | 700 | 0 | 0 | 200 | 3850 | 0 | 0 | 6300 |
| 39 | 150 | 150 | 0 | 0 | 0 | 0 | 0 | 200 | 3850 | 0 | 0 | 6300 |
| 40 | 150 | 150 | 550 | 350 | 0 | 0 | 0 | 200 | 3500 | 0 | 0 | 6300 |
| 41 | 150 | 150 | 400 | 0 | 0 | 0 | 0 | 200 | 3500 | 0 | 0 | 6300 |
| 42 | 150 | 150 | 250 | 0 | 350 | 0 | 0 | 200 | 3500 | 0 | 0 | 6300 |
| 43 | 150 | 150 | 100 | 700 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 14900 |
| 44 | 150 | 150 | 300 | 0 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 14900 |
| 45 | 150 | 150 | 150 | 0 | 700 | 0 | 0 | 200 | 2800 | 0 | 0 | 14900 |
| 46 | 150 | 150 | 0 | 0 | 0 | 0 | 0 | 200 | 2800 | 0 | 0 | 14900 |
| 47 | 150 | 150 | 550 | 350 | 0 | 0 | 0 | 200 | 2450 | 0 | 0 | 14900 |
| 48 | 150 | 150 | 400 | 0 | 0 | 0 | 0 | 200 | 2450 | 0 | 0 | 14900 |
| 49 | 150 | 150 | 250 | 0 | 350 | 0 | 0 | 200 | 2450 | 0 | 0 | 14900 |
| 50 | 150 | 150 | 100 | 700 | 0 | 0 | 0 | 200 | 1750 | 0 | 0 | 14900 |
| 51 | 150 | 150 | 300 | 0 | 0 | 0 | 0 | 200 | 1750 | 0 | 0 | 14900 |
| 52 | 150 | 150 | 150 | 0 | 700 | 0 | 0 | 200 | 1750 | 0 | 0 | 14900 |
| 53 | 150 | 150 | 0 | 0 | 0 | 0 | 0 | 200 | 1750 | 0 | 0 | 14900 |
| 54 | 150 | 150 | 550 | 350 | 0 | 0 | 0 | 200 | 1400 | 0 | 0 | 14900 |
| 55 | 150 | 150 | 400 | 0 | 0 | 0 | 0 | 200 | 1400 | 2450 | 0 | 14900 |
| 56 | 150 | 150 | 250 | 0 | 350 | 0 | 0 | 200 | 1400 | 0 | 0 | 12450 |
| 57 | 150 | 150 | 100 | 700 | 0 | 0 | 0 | 200 | 700 | 0 | 2450 | 12450 |
| 58 | 150 | 150 | 300 | 0 | 0 | 0 | 0 | 200 | 700 | 0 | 0 | 12450 |
| 59 | 150 | 150 | 150 | 0 | 700 | 0 | 0 | 200 | 3150 | 0 | 0 | 12450 |
| 60 | 150 | 150 | 0 | 0 | 0 | 0 | 0 | 200 | 3150 | 0 | 0 | 12450 |

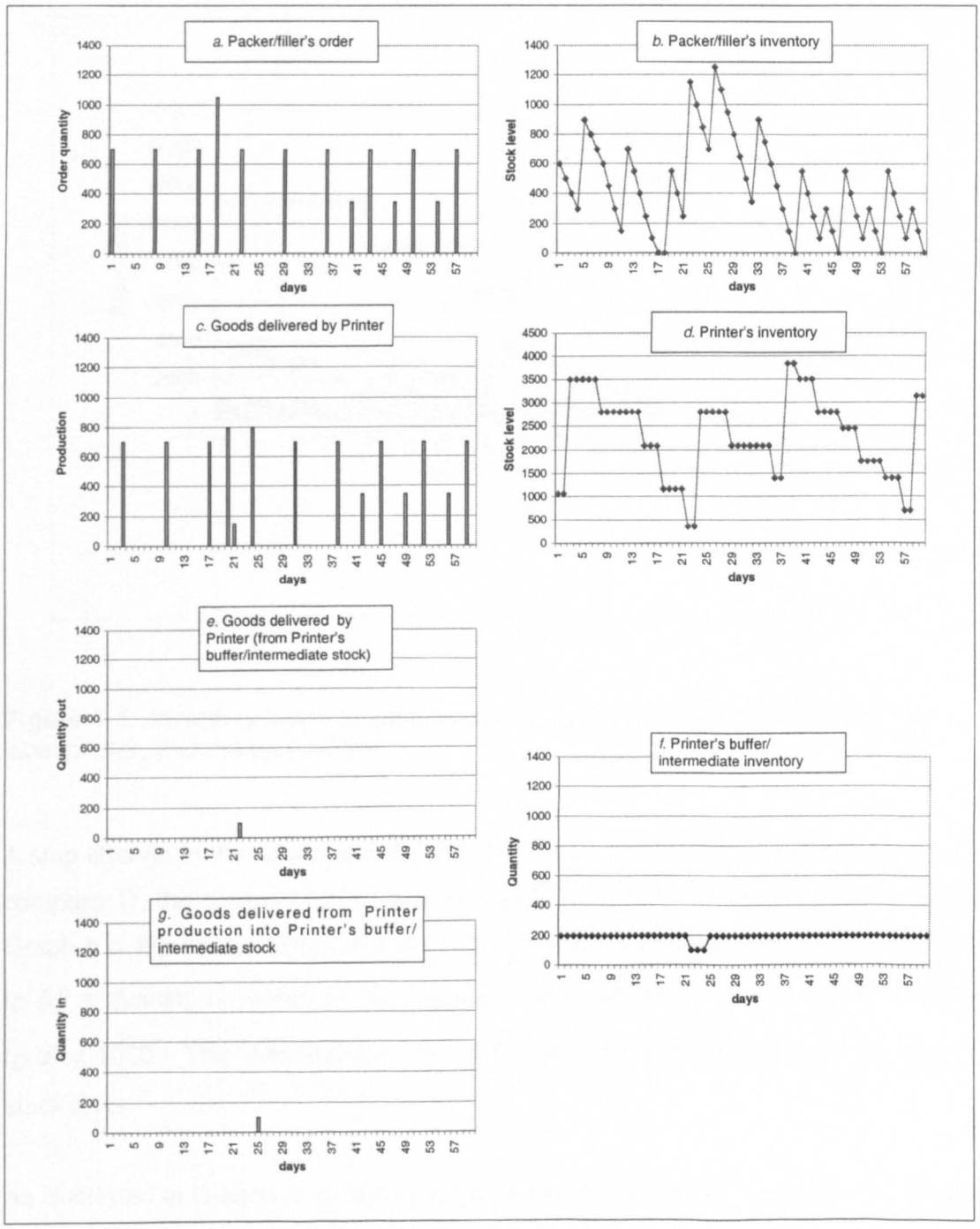



**Figure 4-3** Production rates and inventory levels.

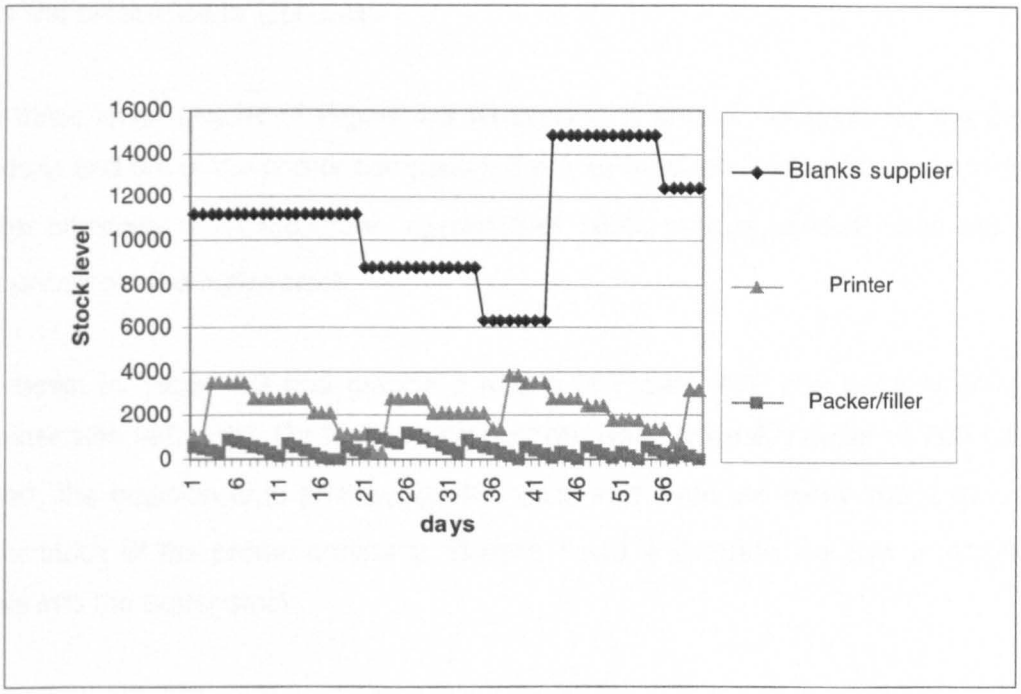



**Figure 4-4**: Inventory levels at each company, the blank label manufacturer, the label printer, and the packer/filler.

A step change in the retailer's order that begins on $d$=9 causes the inventory level at company D, the packer/filler, to drop gradually, and then settle to a new level. See Graph *b* of Figure 4-3. Graph *a* shows that an order is generated on day, $d$=18, when $l_D\ (d)$ + quantity on order. Ie. $s_{D\ threshold}$ .The emergency order is equal $7^{*}u_E(d) - l_D(d) = 1050$ . This demonstrates the action of the inventory policy to regulate the stock level.

As illustrated in Graphs *b, c,* and *d,* an increase in the retailer's order from 100 units to 150 units induces demand variations that are transmitted to company D. As depicted in graph *a,* in many instances, company D has to order more frequently (issue emergency order) to meet demands. This effect is transmitted upstream to company C, who has to produce more frequently to meet the demands by the company downstream. Graph *c* shows the utilization of the printer production where the order, $e$ =1050 units is completed in two consecutive days, that is on $d$=20 the

production is 800 units (equal the maximum capacity of printer production) and on $d$=21 the production is 150 units.

The three lower graphs of Figure 4-3 (Graphs *e, f,* and *g*) demonstrate the flow of goods in and out of the printer company buffer/intermediate stock. The decision at the printer company is for the order $u_D(d=18)$ of 1050, print $p_C(d)$=950 units and take 100 units from the buffer stock.

As shown in Table 4-3 and graphs *c* and *e* of Figure 4-3, 100 units is delivered together with 950 units. On the next production, when a weekly order of 700 units is issued, the decision is to print $p_C(d)$=800 units and send the extra 100 units to the buffer stock of the printer company. Graphs *f* and *g* illustrate the flow in of printed labels into the buffer stock.

Figure 4-4 compares the inventory levels. These graphs, representing the inventories at the three different companies, indicate that a small change in demand at the retailer has given rise to a large demand and inventory fluctuation at the packer/filler. A similar phenomenon is observed for the case of the packer/filler and the printer, as well as for the case between the printer and the blank labels supplier.

Another interesting result could be observed. Graphs *a* and *c* of Figure 4-3, show a delay due to lead time. The variations of the production sizes and the reorder intervals causes company D's inventory to experience oscillations. These graphs indicate that a small changes in demand from the downstream results in large demand and inventory amplifications upstream in the supply chain. These demonstrate the contribution of lead times to the demand amplification effect.

These results provide an indication that the simulation is performing as expected, that is by

(a). *visual checks:* the model output graphs do suggest that the model behaves correctly, and

(b). *inspection of results:* the behavior of the system does match the expectations of the behavior of each element in the model.

## 4.5 Summary

Having given a detailed description of the main procedures involves in the simulation and modelling of a supply chain system using a discrete-event simulation (DES), particularly the development of the conceptual model and its implementation in chapter 3, this chapter describes the next stage in the model development: verification and validation.

This chapter covers the model verification, the validation and the testing procedures conducted, and explains how the results were analysed and discussed. Throughout the modelling process, the variable values and program flow is continuously checked against what would be expected. The purpose is to ensure that the conceptual model has been transformed into a simulation model with sufficient accuracy (verification).

In the context of this work, the model has been verified and is sufficiently accurate for its purpose. Model validation was performed by comparing simulation results to calculations of system equations, and by visual checking and inspection of the model's output. The results suggest that the behavior of the system does match the expectations of the behavior of each element in the model.

A run of a simulation example presented in section 4.4 illustrates how the model could be utilised as an experimental tool to understand the dynamics of the supply chain. Various parameters such as the inventory level, production size, and order size were plotted, and these plots were useful in answering relevant questions such as the effect of delays on the overall supply chain system.

The model was developed with easily modifiable structure that inventory managers at company C, the label printer, or at company D, the packer/filler could evaluate several 'what if' scenarios. Since the model is correlated in time, several complex relationships that occur in the supply chain system could be investigated. Importantly, it is possible to test out many of the proposed on-line and off-line decisions that could not be performed due to the limitations of the more widely used methods, for example the operation research, and classical control.

In the subsequent chapters, this simulation model is to be expanded to allow some performance measurements to be carried out, and to compare the effectiveness of the appropriate decision policies for effective control and co-ordination of the production-inventory systems, involving the printer and the packer/filler companies.

# Chapter 5

# Performance Analysis of Policies in Base model

## 5.1 Introduction

The supply chain has been viewed as a network of facilities that perform the procurement of raw material, the transformation of raw material to intermediate and end products, and the distribution of finished products to retailers. These facilities, which belong to different companies, consist of production plants distribution centres, and end-products inventories. They are integrated in such a way that a change in any one of them affects the performance of others. As has been discussed in Chapter 2, substantial work has been done in the field of optimal supply chain control, using analytical modelling. Various supply chain strategies and different aspects of supply chain management have been investigated, however, most of the developed model study only isolated parts of the supply chain.

This research investigates and analyses a simulation model of a four-echelon chain system based on a packaging industry supply chain that form a part of a fast moving consumer goods (FMCG) supply chain producing to order with fluctuations in demand patterns. As has been discussed in Chapter 3 and Chapter 4, the developed simulation model is shown to provide valuable insights in the understanding of this supply chain system, and facilitates decision-maker to solve some problems, for example formulating effective supply chain policies towards providing better services to end customers.

This chapter gives some examples to illustrate the application of the simulation model in evaluating the effectiveness of several supply chain policies. The simulation model (*Base model*), as described in Chapter 3 and Chapter 4 will be used to test several decision policies (inventory policies), more specifically at the packer/filler company (company D). These policies have been formulated based on observation of real-life processes. The performances of each case will be compared and analysed.

## 5.2 Supply chain performance measures

A large number of performance measures have been used to characterise manufacturing systems, particularly production, distribution and inventory systems. The large number of performance measures available can be categorised into the following groups: time, cost, quality and flexibility. This categorisation is a useful tool in systems analysis. Measures within a category can be compared and analysed, so that performance measure selection within a category may be easier. However, the problem becomes more complicated for a supply chain system, because each individual echelon in the system may use a different performance measurement criteria.

Before starting to analyse a complex supply chain system the following questions should be answered: What to measure? Is each individual echelon from the supply chain based on the same measurement system? How are multiple individual measures integrated into a measurement system? How often to measure? How and when are measures re-evaluated in order to analyse and create the best possible supply chain system?

The supply chain models have predominantly used two different performance measures: (1) cost, and (2) a combination of cost and customer responsiveness. Cost may include inventory cost and operating cost. Customer responsiveness measures include lead-time, stock out probability, and fill rate, see for example Beamon [Beamon 99]. Beamon summarised the performance measures in terms of cost, cost and customer responsiveness, customer responsiveness and flexibility.

The following discussion classifies the main performance measures for a supply chain system and their objectives. The number of the performance measures are larger than that in the table below, and more are used by researchers and practitioners such as increased market share and increased capital turnover. Because it is not the scope of this research to analyse in detail the supply chain performance measures, the comments are limited only to the performances described in Table 5-1.

**Table 5-1** Performance measures and objectives for a supply chain system.

| Performance measures | Objectives |
|---|---|
| ***Cost*** | |
| Total Cost | Min. |
| Distribution Cost | Min. |
| Manufacturing Cost | Min. |
| Inventory Cost | Min. |
| Transportation Cost | Min. |
| Return on Investment | Max. |
| ***Output Measures*** | |
| Number of items produced (throughput) | Max. |
| Number of orders delivery on time | Max. |
| Number of orders delivered with delay | Min. |
| Sales | Max. |
| Profit | Max. |
| Fill Rate | Max. |
| On-time deliveries | Max. |
| Number of Stock-outs | Min. |
| Number of Backorders | Min. |
| ***Customer Responsiveness*** | |
| Customer response time | Min. |
| Manufacturing lead time | Min. |
| Number of customers complaints | Min. |
| ***Flexibility***[a] | |
| Response | Max. |
| Range | Max. |

*Note:*

[a] Flexibility measure may include how well the supply chain system is able to adjust to uncertainties.

*Total Cost*[b] – The total cost of resource used.

*Distribution Cost* – The total cost of distribution.

[b] The definition of total cost is associated with used resources as in the supply chain literature [Beamon 99]

*Manufacturing Cost* – The total cost to manufacture the product; it is also called the processing cost.
*Inventory Cost* – The total cost to hold the inventory; it can be considered as work in progress cost which is the cost associated with the work-in-progress inventories. Also, it can be added to the cost associated with held finished goods inventory (holding cost).
*Transportation Cost* – The total cost for transportation.
*Return on investment* – Measure of the profitability of an organisation.

*Throughput* – The number of items produced.
*Number of orders delivered on time* - The number of orders delivered on or before the due date.
*Number of orders delivered with delay* - The number of orders delivered after the due date.
*Sales* – The total revenue.
*Profit* – The total revenue less expenses.
*Fill rate* – The proportion of orders filled immediately.
*On-time deliveries* – The measures of item, order, or product delivery performance.
*Number of stock-outs* – The number of times requested items are out of stock.
*Number of backorders* – The number of items due to stock-out.

*Customer response time* – The amount of time between an order and its corresponding delivery.
*Manufacturing lead time* – The time required to produced a particular item or batch.
*Customer complaints* – The number of customers complaints registered.

*Flexibility* – The measurements of a system's ability to accommodate volume and schedule fluctuations from suppliers, manufacturers, and customers.

Slack [Slack 91] identifies two types of flexibility; namely, range flexibility and response flexibility. Range flexibility is defined as the extent to which the operation can be changed. Response flexibility is defined as the ease (in terms of cost, time, or both) with which the operation can be changed. Although there will be a limit to the range and response flexibility of a supply chain, the chain can be designed to adapt

adequately to the uncertain environments. Das [Das 96] argues that since every manufacturing facility experiences different changes to different degrees (which is applicable to supply chain as well), and the diversity of these possible changes is large, several types of flexibility may be appropriate.

It is considered that *flexibility*, which is seldom used in supply chain analysis, is vital to the success of the supply chain, since the supply chain exists in an uncertain environment. Beamon [Beamon 99] argues that the performance measures developed so far are inadequate because they rely heavily on the use of cost as a primary measure, and they do not consider the effect of uncertainty. The suggestion is to consider a multiple supply chain performance measure incorporated in the supply chain system. Cost, customer responsiveness and flexibility (how well the system reacts to uncertainty) has been identified as vital components to supply chain success.

The particular work to be conducted in this chapter and the next chapter is to identify and understand the complex relationships that would occur in a supply chain system, for example, in the occurrences of uncertainties, or disturbances. A supply chain may be currently utilising its resources efficiently, and producing the desired output, but will the supply chain be able to adjust to changes for example in product demand, manufacturing unreliability, the introduction of new products, or supplier shortages?

Many of the performance measures are related to each other, hence, the choice of a subset of performance measures for analysis in this chapter. The primary emphasis of the experimental work is placed on evaluating the supply chain performance focusing on the 'flexibility' aspects, where different ordering policies will be compared and analysed. Meaningful analysis must consider the ability of the system to respond to demand variations. Several tests with different input pattern (demand variation's from retailer) will be studied.

## 5.3 Supply chain inventory models

To run a successful inventory system, which should effectively control the supply of replenishment orders against the requirements of demand orders it is clearly necessary to have a policy which defines a series of rules as to how replenishment orders are to be raised. The fundamental purpose of a replenishment control system is to resolve the following three issues, see Silver *et. al.* [SilverPP 98]:

a. How often should the inventory status be determined?
b. When should a replenishment order be placed?
c. How large should the replenishment order be?

The following discussion highlights the five inventory policies, that have been identified for the purpose of this research. The numbers of the inventory policies are larger than that in the discussion below, however, it is not the scope of this research to analyse in detail the supply chain inventory models (policies).

### 5.3.1 Generic policy

The basic policy that was implemented in the case study in chapters 3 and 4 is called a generic policy. It is expressed heuristically as follows: A weekly order is placed with the order quantity equal to a weekly supply, or a seven day supply to retailer. An emergency order is placed on any day of the week if the stock plus the quantity on order declines to a lower limit called the re-order threshold point. The order quantity equals to the difference between a weekly demand and the current stock. A closer look at this policy would suggest that it may be identified as the hybrid of the periodic review (fixed size of weekly order) and the continuous review (variable size of emergency order).

### 5.3.2 (*s*,*S*) policy

This policy dictates that an order be placed when the stock declines to a lower control limit called the order point, *s*. The order quantity is the amount necessary to bring the inventory level to the order level, *S*. The (*s*,*S*) policy assumes continuous review. A

variable replenishment quantity is used, ordering enough to raise the inventory position to the order-up-to-level *S*. It is interesting that (*s,S*) policy is frequently encountered in practice. In most cases mathematical optimality cannot easily be stated through a criteria; instead a fairly simple way of obtaining reasonable values of *s* and *S* were used. In [McCor 78], Mac Cormick used retrospective simulation to study the problem of selecting the control variable *s*, the order point, and *S*, the order level of an (*s,S*) model. Retrospective simulation is a method by which simulation model is tested using available historical data. In the case of an inventory control problem, historical demand can be used to calculate *S*, and *s*. In their book, Silver *et. al.* [SilverPP 98] pointed out the following: One disadvantage of the (*s,S*) policy is the variable order quantity. Suppliers could make errors more frequently; and they prefer the predictability of a fixed order quantity.

### 5.3.3 Smooth average policy

Smooth average policy looks at forecast pattern based on recent orders received in a particular period, and uses it to forecast future orders in formulating the policy. Even though the procedure of calculations is relatively simple and straightforward, the smooth average (or moving average) as a forecasting model for the inventory control has not been widely used. The reasons can be related to the difficulty in initialisation, that is, to start from a situation where no data exist. Also, it requires that relatively large amount of data are to be stored, especially if forecasts are to be provided for several thousand stocked items. Furthermore, it weights all data equally irrespective of their age; whereas simple logic would suggest that more recent data should be weighted heavily than older data [Lewis 01].

### 5.3.4 Pseudo PID policy

The underlying specific mechanism of applying this policy as an inventory model in a supply chain system has not been reported. The thrust of the idea for proposing this policy in this thesis comes from the control system representation and the use of feedback. Feedback has often had revolutionary consequences with drastic improvements in performance, see Bennett [Bennett 93]. The PID controller is by far the most dominating form of feedback in use today and is used in wide range of

problems, see Astrom and Hagglund [AstromH 01]. An analogy to inventory control would be in the design of a controller that keeps process variables within range: a typical situation for level control in surge tanks where it is desired that the level changes but it is not permitted either to have the tanks flooded or to have them empty. The way of how the pseudo PID policy work is summarised as follows: An order is placed when the stock declines to a lower control limit, *s*. The actual order is obtained from its desired value, after taking the physical limits of the inventory system and its dynamics, and subjected to the control law. As with the PID controller to improve steady-state error, the value of the order is adjusted accordingly using the expression representing the controller action, see Table 5-2 in section 5.4.2.

### 5.3.5 Vendor-managed inventory (VMI) policy

According to this policy (strategy), the supplier is authorised to create and maintain the inventory of the customer (retailer) for example, generating the purchase orders. The supplier has access to the necessary inventory and sales information, authority and responsibility to manage the customer's inventory.

Blatherwick [Blath 98] pointed out that the strategy is effective when the relationship between major retailers and major suppliers is constructive and open, and the party who is most able and in the best position to manage the supply relationship is in control of the supply chain. Using a simulation model, Johnson *et. al.* [JohnDW 99] examined the impact of VMI in less-than-ideal environment, such as those with high demand volatility, partial adoptation of VMI, and limited manufacturing capacity. They assumed that VMI only involved the reduction in ordering frequency from retailers to the supplier. They showed that the VMI approach greatly reduced inventories for all participants in the supply chain without compromising service.

The main objective of the study presented in this chapter is to investigate the effect of the decisions (inventory policies) on the performance of two specific players in the supply chain system: the packer/filler, and the printer. The relevant algorithms for the above supply chain models (policies) researched, are presented in detail in section 5.4.2.

## 5.4 Problem formulation

The following main notation will be applied. This is similar to the notations defined in Table 3-1.

**Nomenclature**

| Notation | Description |
|---|---|
| $x$ | Subscript indicating company $x$={A \| B \| C \| D \| E } |
| $i$ | Day of the week index ($i=0$ indicates Sunday), $i$=0,…,6 |
| $w$ | Week number index, $w$= 0, 1,…,$W$ |
| $d$ | Day number index (numbering starts from start of simulation) $d=(7w+i)$ or, $d$=0,1,…,$D$ |
| $E$ | Number of emergency orders set to printer |
| $e$ | Size of emergency order sent to printer |
| $l_x(d)$ | Inventory level of printed labels at company $x$ on day $d$ |
| $p_x(d)$ | Production at company $x$ on day $d$ |
| $S_x$ | Order-up-to-level for company $x$ |
| $s_x$ | Re-order level for company $x$ |
| $ss_x$ | Minimum stock level for company $x$ |
| $u_x(d)$ | Order placed by company $x$ on day $d$ |
| $V_D(w)$ | Average variation in weekly orders placed by company D measured at week $w$ |
| $y_x(d)$ | Goods delivered by company $x$ on day $d$ |

Additional notation will be introduced where necessary.

### 5.4.1 The Base Model description

The basic model assumptions are:

Steady state: order from retailer (E) to packer/filler (D) $u_E$(d) = 100 units per day.

Inventory policy at packer/filler: Generic policy.

Minimum stock level for deterministic demand (safety stock level) at packer/filler $ss_D$ = 300 units.

Re-order level at packer/filler $s_D = ss_D$ + LT x 100 units/day = 600, where LT is the lead time = 3 days.

Order from packer/filler (D) to printer (C) once per week $u_D$ = 700 units, the regular order is sent on day, $i = 0$, that is Sunday.

In addition to the weekly Sunday order, an order is sent if the stock level plus the quantity on order, falls to or below a threshold re-order level, $s_{D\ threshold}$.

or,

$$l_D(d) + \sum_{i=0}^{d}[y_C(i) - u_D(i)] \leq s_{D\ threshold}$$

where $s_{D\ threshold} = (S_D - (ss_D - u_E(d)))$,

*make an order for quantity,* $e = 7^* u_E(w+i) - I_D(7w+i)$ *to replenish the stock level.*

Printer (company C) can produce 100 units per hour and printer operates 1 shift of 8 hours each day. Delivery delay printer to packer/filler is 3 days.

Printer keeps between 100 and 200 units of printed labels.

Printer uses *(s,S) policy* for ordering blanks from blanks supplier.

Order from printer (C) to blanks supplier (B) is sent if stock level plus quantity on order falls below $s_C$, where $s_C$ = 700 * 2 + 700 * 1.5 = 2450 units of blanks.

$Q_C$ = 2450 units, and $S_C$ = 4900 units.

In addition to the blank labels stock, there is also a buffer stock of printed labels in company C to hold a stock of printed labels. The quantity is typically between 100 and 200 units. The inventory policy is that sufficient labels are held in stock to meet needs of a sudden increase in order from packer/filler.

The control decision is as follows:

If buffer stock.le.100 units, print $p_C(d)=y_D(d)$+100 units and add 100 units to buffer stock. If buffer stock.ge. 200 units, print $p_C(d)=y_D(d)$-100 units and take 100 units from buffer stock.

Blanks supplier uses *(s,S) policy* for ordering paper and substrates from raw material supplier.

Order from blanks supplier ( B ) to raw material supplier (A) is sent if stock level plus quantity on order falls below $s_B$, where $s_B$ = 2450 * 2 + 2450 * 1.5 = 8575 units of blanks. In the model $s_B$ is set equal to 8600 units. $Q_B$ = 8600 units, and $S_B$ = 17200 units.

### 5.4.2 Description of policies implemented at the packer/filler company.

Policy (a), the generic policy, is assumed being implemented in the existing system. Policies (b), the (*s,S*), and (e), the VMI, are based on the usual practices in most firms. Policies (a), (b), and (e) can be grouped as heuristics. Policies (c), the smooth averaged, and (d), the pseudo PID, are based on certain system principles.

a. *Generic policy* :

A weekly order is placed with the order quantity equal to a weekly supply, or a seven day supply to retailer. An emergency order, *e*, is placed on any day of the week if the stock plus the quantity on order declines to a lower limit called the re-order threshold point. The order quantity is equal to the difference between a weekly demand and the current stock.

b. *(s,S) policy*:

According to this policy, a weekly order is placed when the stock declines to a lower control limit called the re-order point, *s*. The order quantity is the amount necessary to bring the inventory level to the level, *S*. An emergency order, *e*, is placed on any day of the week if the stock plus the quantity on order declines to a lower limit called the re-order threshold point.

c. *Smooth average policy*:

A weekly order is placed with the order quantity equal to the average demand of the last seven days (based on a week average). An emergency order, *e*, is placed on any day of the week if the stock plus the quantity on order declines to a lower limit called the re-order threshold point. The order quantity is equal to the product of the average daily demand with the difference between the number of moving average samples and the day of the week of when the order is issued.

d. *Pseudo PID*:

An order is placed when the stock declines to a lower control limit, $s$, as described in the equations as given below. $k_p$, $k_i$, and $k_d$ represent the proportional, integral, and derivative gains, respectively. The actual order is obtained from its desired value, after taking the physical limits of the inventory system and its dynamics. An emergency order, $e$, is placed on any day of the week if the stock plus the quantity on order declines to a lower limit called the re-order threshold point.

*e.* *Vendor-managed inventory*:

The upper echelon is authorised for creating and maintaining the inventory of the lower echelon for example, generating the purchase orders at regular intervals. The upper echelon has access to the inventory of the lower echelon and uses this information along with the purchase orders information in deciding on the quantity for production.

The policies description given above were translated into their corresponding mathematical equations, and is presented in Table 5-2. Column 1 lists the test models, and column 2 lists the respective mathematical equations of the corresponding policies.

**Table 5-2:** Test models, ordering policies and the respective mathematical equations

| *Model* | *Ordering decision at packer/filler* |
|---|---|
| a. Generic policy | $u_D(7w+i)=\begin{cases}7u_E(7w+i), i=0\\ e, \quad i\neq 0\end{cases}$ |
| b. (*s, S*) policy | $u_D(7w+i)=\begin{cases}7*u_E(7w+i)+[s_D-l_D(7w+i)], i=0\\ e, \quad i\neq 0\end{cases}$ |
| c. Smoothed (average of past orders) k=1 one week. | $u_D(7w+i)=\begin{cases}\frac{1}{k}\sum_{j=1}^{7k}u_E(7w+i+j), i=0\\ e, \quad i\neq 0\end{cases}$ |
| d. Pseudo PID | $i=0$<br>$u_D(7w+i)=k_p*7u_E(7w+i)+$<br>$k_i\sum_{j=1}^{n}[s_D-l_D(7w+i+j)]+$<br>$k_d[u_E(7w+i)-u_E(7w+i-1)]$<br>$i\neq 0$ then $u_D(7w+i)=e$ |
| e. VMI | $p_C(d)=\begin{cases}\max(3*u_E(d), 7*u_E(d)-I_D(d)), i=0,4\\ 0, \quad i\neq 0,4\end{cases}$<br>*Note:* In general, quantity delivered is equal to $p_C(d)$, like for other policies where quantity released is equal to $u_D(d)$. |

In the above the value of *e* is computed, with $s_{D\ threshold} = (S_D - (ss_D - u_E(d)))$, as follows:

a. Generic policy,

$$e=\begin{cases}7u_E(7w+i)-l_D(7w+i), \text{ if } l_D(d)\leq s_{D\ threshold} + \sum_{i=0}^{d}[u_D(i)-y_C(i)]\\ 0, \text{ if } l_D(d)>s_{D\ threshold}\end{cases}$$

b. (*s,S*) policy,

$$e = \begin{cases} 7u_E(7w+i) + ss_D - l_D(7w+i), if\ l_D(d) \le s_{D\,threshold} + \sum_{i=0}^{d}[u_D(i) - y_C(i)] \\ 0, if\ l_D(d) > s_{D\,threshold} \end{cases}$$

c. Smooth average policy,

$$e = \begin{cases} \frac{(7-i)}{7k}[u_E(7w+i) + u_E(7w+i-1) + u_E(7w+i-2) + \ldots + u_E(7w+i-6)], \\ \quad if\ l_D(d) \le s_{D\,threshold} \quad + \sum_{i=0}^{d}[u_D(i) - y_C(i)] \\ 0, if\ l_D(d) > s_{D\,threshold} \end{cases}$$

d. Pseudo PID policy,

$$e = \begin{cases} 7u_E(7w+i) - l_D(7w+i), if\ l_D(d) \le s_{D\,threshold} + \sum_{i=0}^{d}[u_D(i) - y_C(i)] \\ 0,\ if\ l_D(d) > s_{D\,threshold} \end{cases}$$

Note that for VMI, the printer company is authorised for creating and maintaining the inventory at the packer/filler company. [The decision is to produce twice a week, and it was observed that emergency order is not relevant in this case].

### 5.4.3 Description of the model performance measures and objectives.

The ability to understand the influence of the different ordering policies on the performance of the production-inventory system, particularly at the packer/filler and the printer companies, is one of the important purposes of this research. There are many different patterns of retailer orders (each pattern exhibits different scenarios), and each pattern should allow the characteristics of the process (production sizes, inventory levels, order sizes), that are important in understanding the impact of each policy on the system to be analysed. A pulse input, a step input, a sine (sinusoidal) input, and a random input patterns for the retailer orders, as illustrated in Figure 5-1, are good patterns for this purpose.

Test inputs

(a) Equivalent of pulse: step increase held for 7 days then return to initial value. Step increase 50%, that is $u_{Emax}$=150

(b) Step. Step size 50% above set point. ($u_E$ steps from 100 to 150 units).

(c) Sinusoidal with period of 18 days. 20% variation from normal value. ($u_{Emin}$=80, $u_{Emax}$ =120)

(d) Random (maximum variation 30% from set level)

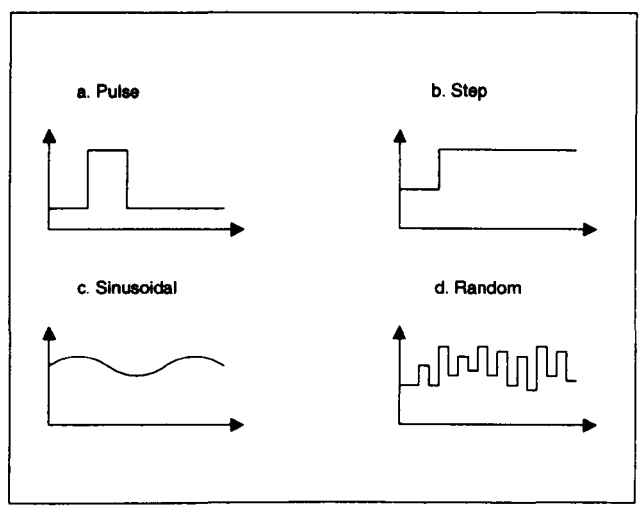



**Figure 5-1.** The patterns for retailer orders.

The following performance metrics (measures) have been defined for measuring the effectiveness and the efficiency of the supply chain, in meeting the objectives. Different ordering policies will be applied at the packer/filler company and their performances will be taken for analysis and comparison.

Performance metrics (measures)

- **Pulse input**
  - Time to return to steady state [c]
  - Average variation in order quantity set to printer.

$$V_{Dav} = \frac{1}{n} \sum_{w=1}^{n=\lfloor d/7 \rfloor} \left| u_p(w) - u_p(w-1) \right|$$

$\lfloor d/7 \rfloor$ gives the quotient and is an integer.

[c] The system is assumed to have reached steady state when the difference in the parameter values over two successive weekly patterns is exactly zero.

- Number of orders.
- Number of emergency orders *E* at day d

$$E = \sum_{i=0}^{d} I(i)$$

$$I(i) = \begin{Bmatrix} 1, \text{ if } u_D(d) \neq 0 \text{ AND } i \neq 0 \\ 0 \end{Bmatrix}, i = 1 \ldots d$$

*Note*: The variation in order quantity to printer, the risk of stock-out, and the downstream demand amplification are not included as performance measures in this case, because the short duration of the disturbance does not impact on these measures.

- **Step Input**
  - Time to reach steady state
  - Average stock levels at D $l_{Dav}$ and C $l_{Cav}$

$$l_{Dav} = \frac{1}{d}\sum_{i=0}^{d} l_D(i)$$

$$l_{Cav} = \frac{1}{d}\sum_{i=0}^{d} l_C(i)$$

  - Variation in order quantity to printer.

$$V_{Dav} = \frac{1}{n}\sum_{w=1}^{n=\lfloor d/7 \rfloor} \left| u_p(w) - u_p(w-1) \right|$$

  - Number of orders.
  - Number of emergency orders, *E*
  - Risk of stock out (use number of stock-outs per 100 days as measure).
  - Downstream demand amplification, Var ($u_D$) / Var ($u_E$) (the variance of the orders placed by packer/filler to printer over the variance of the orders placed by retailer to packer/filler).

- **Sinusoidal input**
  - Average stock levels at packer/filler, $l_{Dav}$ and printer, $l_{Cav}$

$$l_{Dav} = \frac{1}{d}\sum_{i=0}^{d} l_D(i)$$

$$l_{Cav} = \frac{1}{d}\sum_{i=0}^{d} l_C(i)$$

- Maximum and minimum stock levels at D (packer/filler) and C (printer), $l_{D\,max}$, $l_{D\,min}$, $l_{C\,max}$, $l_{C\,min}$.
- Maximum order quantity to printer, $u_{Dmax}$.
- Variation in order quantity to printer.

$$V_{Dav} = \frac{1}{n} \sum_{w=1}^{n=\lfloor d/7 \rfloor} \left| u_p(w) - u_p(w-1) \right|$$

- Number of orders.
- Number of emergency orders, $E$
- Risk of stock-out (use number of stock-outs per 100 days as measure).
- Downstream demand amplification, Var ($u_D$) / Var ($u_E$) (the variance of the orders placed by packer/filler to printer over the variance of the orders placed by retailer to packer/filler).

- **Random input**
  - Average stock levels at packer/filler, $l_{Dav}$ and printer, $l_{Cav}$

$$l_{Dav} = \frac{1}{d} \sum_{i=0}^{d} l_D(i)$$

$$l_{Cav} = \frac{1}{d} \sum_{i=0}^{d} l_C(i)$$

  - Maximum and minimum stock levels at D (packer/filler) and C (printer), $l_{D\,max}$, $l_{D\,min}$, $l_{C\,max}$, $l_{C\,min}$.
  - Maximum order quantity to printer, $u_{Dmax}$.
  - Variation in order quantity to printer.

$$V_{Dav} = \frac{1}{n} \sum_{w=1}^{n=\lfloor d/7 \rfloor} \left| u_p(w) - u_p(w-1) \right|$$

  - Number of orders.
  - Number of emergency orders, $E$
  - Risk of stock out (use number of stock-outs per 100 days as measure).
  - Downstream demand amplification, $Var(u_D)$ / $Var(u_E)$ (the variance of the orders placed by packer/filler to printer over the variance of the orders placed by retailer to packer/filler).

The detail descriptions and objectives of the performance metric (measures) to be used in this study is presented in Table 5-3.

**Table 5-3** Performance measures, descriptions, and objectives for the model.

| Performance measures | Descriptions | Objectives |
|---|---|---|
| Time to reach steady state | The ideal response of the packer/filler's inventory level to a step change in demand (retailer's orders) is that it should react as quickly as possible in adapting to the post step change level of demand, or recover to consistent conditions following disturbance. | Min. |
| Maximum and minimum stocks level | The inventory level is to be sustained at a low level, without compromising service level. | Within range. |
| Average stocks levels | The inventory level is to be sustained at a low level. | Min. |
| Maximum order quantity to printer | The order quantity is to be sustained at a low level. | Min. |
| Average variation in order quantity set to printer | The order variations should be kept small, since this can mean that the replenishments are made on a regular basis with small variations in the order sizes. | Min. |
| Number of emergency orders | The number of emergency orders is to be kept low, since this can mean that the extra cost incurred in the replenishments can be minimised. | Min. |
| Risk of stock out | Risk of stock out is to be kept low, since this reflects the ability to offer a reasonable level of service to the customer. | Min. |
| Demand amplification | The increase in variability that occurs at every stage of the supply chain. | Min. |

## 5.5 Description of the test model

The objective here is to use the simulation model to understand how a complex system such as a supply chain system, which is difficult to analyse analytically, behaves in different situations by varying the input parameters. The simulation model

allows the modeller to modify the coding, at a section of the program (representing the decision policy at the packer/filler company) when performing the tests.

Figure 5-2 shows the supply chain configuration for cases when implementing the generic policy, (*s,S*) policy, smooth averaged policy, and pseudo PID policy. Figure 5-3 shows the supply chain configuration for the case when implementing the vendor-managed inventory policy. Except for vendor-managed inventory policy, for the other cases, the packer/filler company has access to information like the retailer's order, and the stock level at the packer/filler inventory.

As illustrated, the packer/filler makes its own decision on how much to order by generating the order quantity based on the decision policy. For vendor-managed inventory, the printer company is responsible for creating and maintaining the packer/filler's inventory. The printer company has access to the packer/filler inventory data and is responsible for generating the purchase orders. As shown in Figure 5-2 and Figure 5-3, for all cases, the order generated by the retailer is issued directly to the packer/filler.

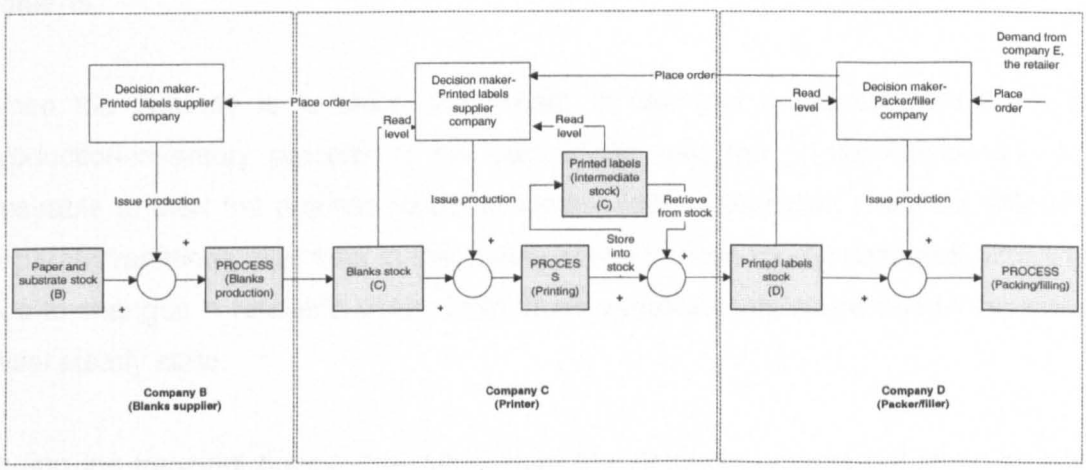



**Figure 5-2.** The supply chain configuration: cases for implementing the *generic policy, (s,S) policy, smooth average policy,* and *pseudo PID policy*

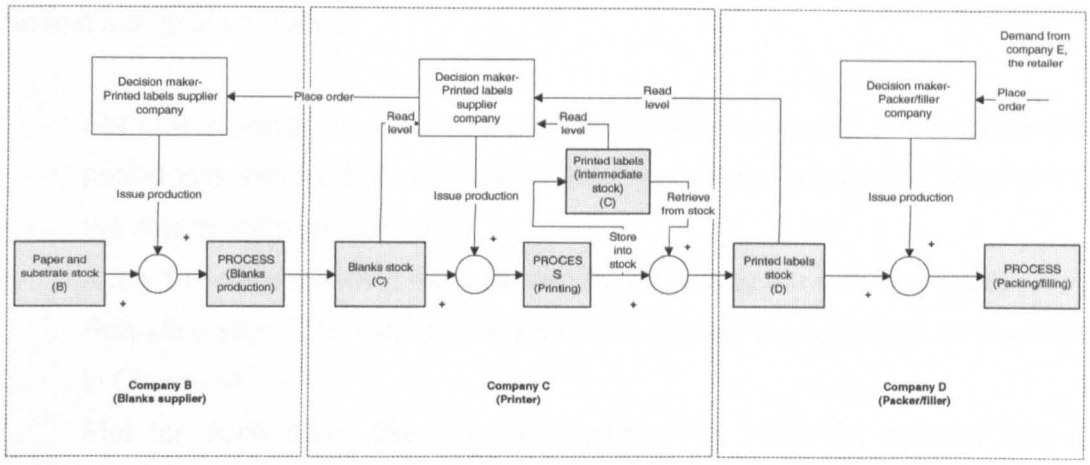



**Figure 5-3.** The supply chain configuration: case for implementing the *vendor-managed inventory policy.*

Simulations were conducted to understand the contribution of each ordering policy implemented at packer/filler to the various parameters like the production sizes and inventory levels, as well as the demand amplification effect. No changes were made to the decision policies implemented at the printer company and the blanks supplier company. The different ordering patterns from the retailer, considered as the input to the system, were assumed to be of the pulse, the step, the sine and the random patterns.

Since the purpose is to study the impact of changes in retailer's order on the production-inventory process of the packer/filler and the printer companies, it is desirable to start the process model in steady state. Otherwise, it will be difficult to separate variations over time in the values of the various model variables, which are due to changes in retailer's orders from those variations which are due to the lack of initial steady state.

During the transient period, the output from the simulation model will show an initial period in which the values are low but have an upward trend, followed by a series of observations that vary around some fixed mean (steady state period). The initial transient period is excluded from the results. During the steady state, for example the inventory levels are expected to display steady state behaviour with a fixed mean. A steady state condition can be detected by examining the inventories in the model. In steady state, the sum of all inflows to each inventory equals to the sum of all outflows.

The test set-up is as follows:

a. Start the process model in steady state. In this simulation, the initial transient period was excluded. The first simulation day ($d$=1), as adjusted to conform to the steady state conditions.
b. Apply the corresponding input pattern (representing the retailer orders)
c. Run simulation. The outputs were validated using the approach as discussed in Chapter 4.
d. Plot for each case, the important graphs, for example, representing the inventory levels at the packer/filler and the printer, the orders from packer/filler and the production at the printer, respectively. Tabulate the corresponding performance measures (metrics).
e. Analyse and interpret the results.

## 5.6 Experiments

This section illustrates the application of the 'Base model' to evaluate the effectiveness of several supply chain policies namely, the generic, the ($s$,$S$), the smooth average, the pseudo PID, and the VMI.

The main purpose of these policies is to act as controllers to countermeasure against disturbances due to fluctuations in the daily orders from retailer. The aim is to have a controller (decision policy) that keeps the process variable, that is, the inventory level within a desired range.

Basically, it is desirable that the inventory level changes but that it be permitted not to exceed a maximum level or to become empty. By generating specific patterns to mimic the forecast data of the daily orders from the retailer representing the load disturbance to the packer/filler company, the resulting fluctuations in the inventory level of each policy could be predicted.

### 5.6.1 The first Test model: Pulse input

The pulse is an example of a short term change in demand pattern, for example a sudden surge in demand for the product prior to a festival.

Plots for the production rates and inventory levels of the system with the pseudo PID policy (at packer/filler) in response to a pulse change in retailer's demand, is presented in Figure 5-4.

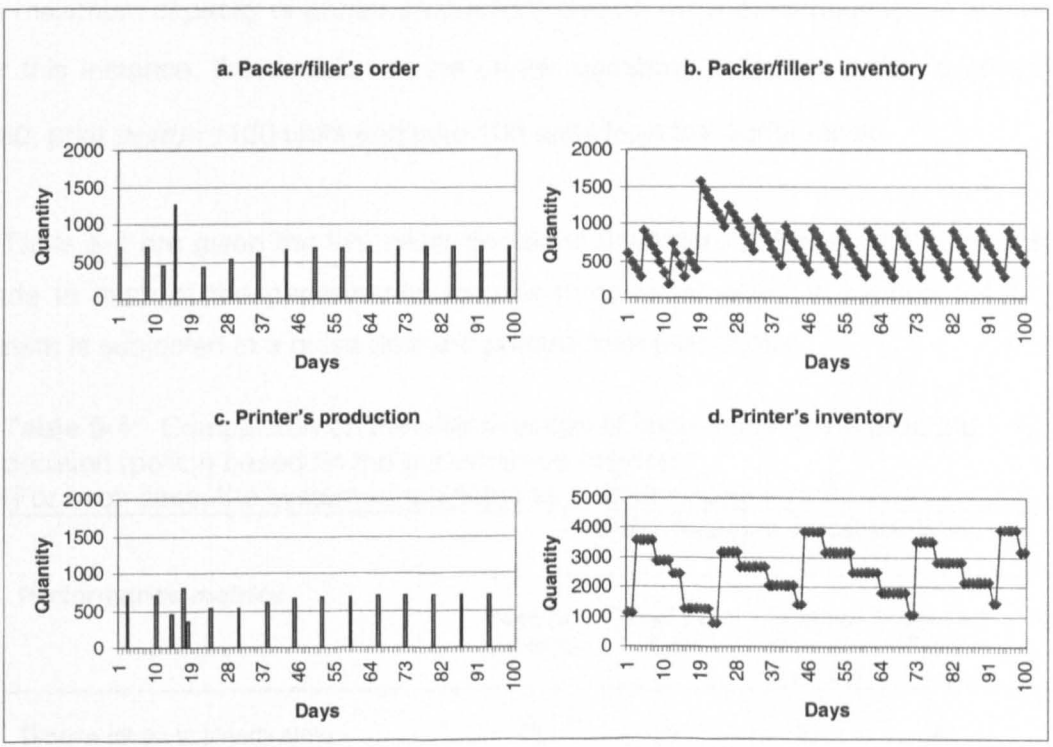



**Figure 5-4**. Production rates and inventory levels of the system with pseudo PID policy (at packer/filler) in response to a pulse change in retailer's demand.

A pulse change in the retailer's order (from $d$=9 until $d$=15) causes the inventory level at company D, the packer/filler, to drop gradually and rise to peak level, and then settle slowly to a new level. See Graph *b* of Figure 5-4. Graph *a* shows that an order is generated on day, $d$=12, when $I_D\ (d)$ + quantity on order. Ie. $s_{D\ threshold}$ .The emergency order is equal $7^{*}u_E(d) - I_D(d) = 300$. This demonstrates the action of the inventory policy to regulate the stock level.

As illustrated in Graphs *b, c,* and *d* of Figure 5-4, an increase in the retailer's order from 100 units to 150 units induces demand variations that are transmitted to company D. As depicted in graph *a,* in one instance, company D has to issue an emergency order (300 units), followed by a large weekly order (1260 units) to meet demands. This effect is transmitted upstream to company C, who has to produce more frequently to meet the demands by the company downstream.

Graph *c* shows the utilization of the printer production where the order of 1260 units is completed in two consecutive days, that is on $d$=17 the production is 800 units (equal the maximum capacity of printer production) and on $d$=18 the production is 360 units. For this instance, the decision at the printer company is for the order, $u_D(d=15)$ of 1260, print $p_C(d)$= 1160 units and take 100 units from the buffer stock.

In Table 5-4 are given the five order decisions (inventory policies) with comparisons made in each of the performance metrics (measures) given in section 5.4.3. The system is subjected to a pulse demand pattern from the retailer.

**Table 5-4**: Comparison on the effectiveness of implementing the ordering decision (policy) based on the performance metrics.
(For each case, the system is subjected to a similar pulse input)

| **Performance metrics** | **Order decision at packer/filler, $u_D$** | | | | |
|---|---|---|---|---|---|
| | **Test I-a** *Generic* | **Test I-b** *(s,S)* | **Test I-c** *Smooth averaged* | **Test I-d** *Pseudo PID* | **Test I-e** *VMI* |
| Time to return to steady state (in days) | 18 | 25 | 11 | 46 | 28 |
| Average variation in order quantity set to printer | 10 | 210 | 70 | 169 | 230 |
| Number of orders at day d | 16 | 15 | 15 | 16 | 29 |
| Number of emergency orders, E at day d | 1 | 1 | 0 | 1 | *NR* |

*Note:*
*NR- not relevant, since no emergency order is generated.*

The fastest time to return to steady state and the least number of emergency orders made is by the smooth average policy. The generic policy has the better average

variation in order quantity set to printer. The (*s,S*) and the smooth average policies have the better performance, but the generic and the pseudo PID policies are also good, when comparing the number of orders made.

### 5.6.2 The second Test model: Step input

The step is an example of a series of successive demands that are significantly higher or lower than normal which in effect produces two stationary demand situations – one before the step change followed by another stationary situation at a different level subsequent to step change. An example of a step increase in demand could be exhibited when a competitor to the retailer ceases to trade.

Plots for the production rates and inventory levels of the system with smooth average policy (at packer/filler) in response to a step change in retailer's demand, is illustrated in Figure 5-5.

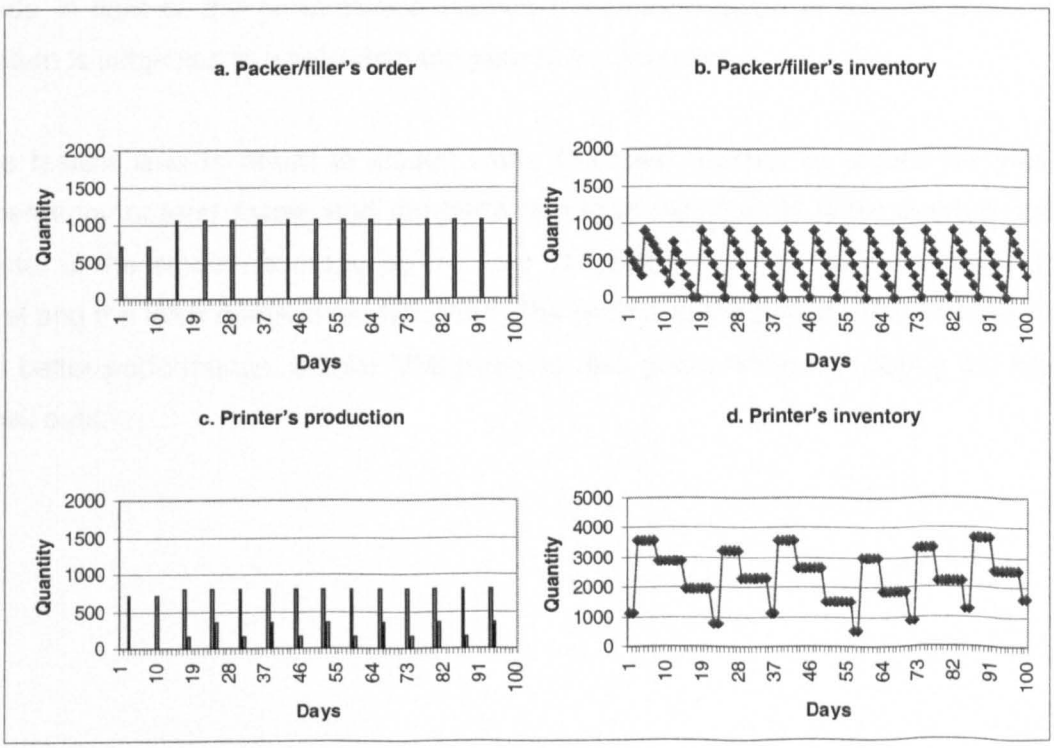



**Figure 5-5.** Production rates and inventory levels of the system with Smooth average policy (at packer/filler) in response to a step change in retailer's demand.

A step change in the retailer's order that begins on $d$=9 causes the inventory level at company D, the packer/filler, to drop and then settle to a new level. The weekly orders made are shown to be greater than the previous orders, that is, before the step rise in orders. However, in this case it shows that no emergency orders are issued ( since it does not satisfy the condition that, $I_D(d)$ + quantity on order. Ie. $s_{D\ threshold}$ ).

As illustrated in Graphs *b, c,* and *d,* an increase in the retailer's order from 100 units to 150 units induces demand variations that are transmitted to company D. As depicted in graph *a,* in many instances, company D has to order more to meet demands. This effect is transmitted upstream to company C, who has to produce more frequently to meet the demands by the company downstream. Graph *c* shows the utilization of the printer production.

In Table 5-5 are given the five order decisions (inventory policies) with comparisons made in light of the performance metrics (measures) given in section 5.4.3. The system is subjected to a step demand pattern from retailer.

The fastest time to return to steady state, the least number of orders (as well as emergency orders) made, and the better average variation in order quantity set to printer is the smooth average policy. The VMI policy has the better average stock level and the least demand amplification. The (*s,S*) and the pseudo PID policies have the better performance, but the VMI policy is also good, when comparing the risk of stock outs.

**Table 5-5.** Comparison on the effectiveness of implementing the ordering decision (policy) based on the performance metrics.
(For each case, the system is subjected to a similar step input)

| Performance metrics | Order decision at packer/filler, $u_D$ | | | | |
|---|---|---|---|---|---|
| | **Test II-a** *Generic* | **Test II-b** *(s,S)* | **Test II-c** *Smooth averaged* | **Test II-d** *Pseudo PID* | **Test II-e** *VMI* |
| Time to return to steady state (in days) | 32 | 16 | 11 | 53 | 14 |
| Average stock levels | | | | | |
| at D $I_{Dav}$ ,and | 369.5 | 639 | 457.5 | 620 | 450 |
| at C $I_{Cav}$ | 2377 | 2303 | 2426 | 2177 | 2429 |
| Average variation in order quantity set to printer | 385 | 245 | 35 | 119 | 380 |
| Number of orders, at day *d* | 25 | 16 | 15 | 16 | *29* |
| Number of emergency orders, E at day *d* | 10 | 1 | 0 | 1 | *NR* |
| Risk of stock out (use number of stock-outs per 100 days as measure). | 11 | 0 | 13 | 0 | 1 |
| Demand amplification | 401.85 | 721.65 | 709.1 | 717.6 | 326.9 |

*Note:*
*NR- not relevant, since no emergency order is generated.*

### 5.6.3 The third Test model: Sinusoidal input

The sinusoidal demand pattern is used to simulate the retailer orders that are influenced by seasons of the year and by other events which occur annually. The retailer's order exhibits a pattern such that the demand in a particular period is higher or lower than a typical average period.

Plots for the production rates and inventory levels of the system with (*s,S*) policy (at packer/filler) in response to a sinusoidal change in retailer's demand, is shown in Figure 5-6.

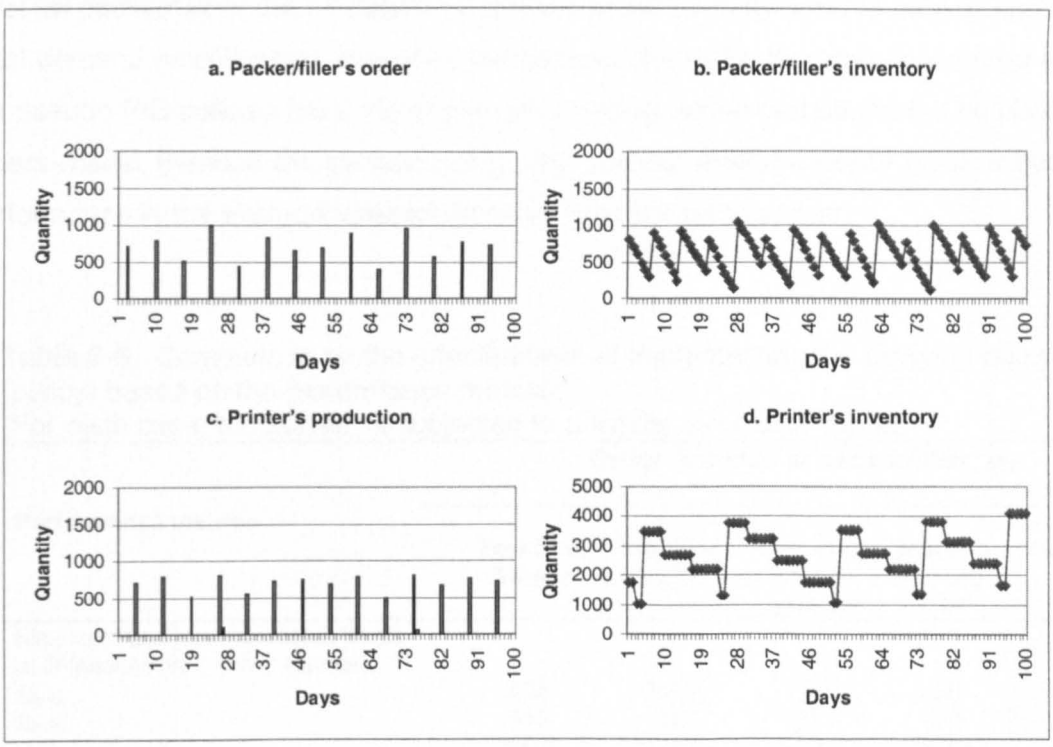



**Figure 5-6.** Production rates and inventory levels of the system with (*s,S*) policy (at packer/filler) in response to a sinusoidal change in retailer's demand.

A sinusoidal change in the retailer's order that begins on *d*=9 causes the inventory level at company D, the packer/filler, to be within range: it is not permitted either to have it too high or to have it empty. The weekly orders made are shown to be changing. Also, it shows that no emergency orders are issued.

As illustrated in Graphs *b, c,* and *d,* the sinusoidal change in the retailer's order induces demand variations that are transmitted to company D. As depicted in graph *a,* in many instances, company D has to either order more, or to order less, to meet demands. This effect is transmitted upstream to company C, who has to produce more, or to produce less, to meet the demands by the company downstream. Graph *c* shows the utilization of the printer production.

In Table 5-6 are given the five order decisions (inventory policies) and the corresponding performance metrics (measures). The system is subjected to a sinusoidal demand pattern from retailer. The VMI policy has the best average stock

level (at packer/filler), the smallest in maximum order quantity send to printer, and the least demand amplification. However, the generic, the (*s,S*), the smooth average and the pseudo PID policies have the better performance, when comparing the number of orders made. Besides the generic policy, the smooth average policy gives a better performance in the average variation in order quantity set to printer.

**Table 5-6.** Comparison on the effectiveness of implementing the ordering decision (policy) based on the performance metrics.
(For each case, the system is subjected to a similar sinusoidal input)

| **Performance metrics** | **Order decision at packer/filler, $u_D$** | | | | |
|---|---|---|---|---|---|
| | **Test III-a** *Generic* | **Test III-b** *(s,S)* | **Test III-c** *Smooth averaged* | **Test III-d** *Pseudo PID* | **Test III-e** *VMI* |
| Maximum and minimum stock levels at D (packer/filler) and C (printer). | | | | | |
| $I_{Dmax}$ | 900 | 1040 | 950 | 1020 | 620 |
| $I_{Dmin}$ | 240 | 120 | 240 | 100 | 50 |
| $I_{Cmax}$ | 3850 | 4120 | 3900 | 3930 | 4200 |
| $I_{Cmin}$ | 1050 | 1050 | 1100 | 1150 | 1430 |
| Average stock levels at D (packer/filler) $I_{Dav}$ and | 576 | 602 | 602 | 588 | 339 |
| at C (printer) $I_{Cav}$ | 2583 | 2702 | 2656 | 2660 | 2830 |
| Maximum order quantity to printer, $u_{Dmax}$. | 700 | 1000 | 770 | 980 | 660 |
| Average variation in order quantity set to printer. | 0 | 278.6 | 80.7 | 239.3 | 258.5 |
| Number of orders, at day d | 14 | 14 | 14 | 14 | 29 |
| Number of emergency orders, *E* at day d | 0 | 0 | 0 | 0 | 0 |
| Risk of stock out (use number of stock-outs per 100 days as measure). | 0 | 0 | 0 | 0 | 0 |
| Demand amplification | 391.3 | 426.6 | 383 | 419.1 | 177 |

### 5.6.4 The fourth Test model: Random input

The random demand pattern is used to simulate the retailer orders that exhibit unpredictable behaviour. An example of a random demand could be when the demand for the product fluctuates very frequently.

Plots for the production rates and inventory levels of the system with VMI policy (at packer/filler) in response to a random change in retailer's demand, is given in Figure 5-7.

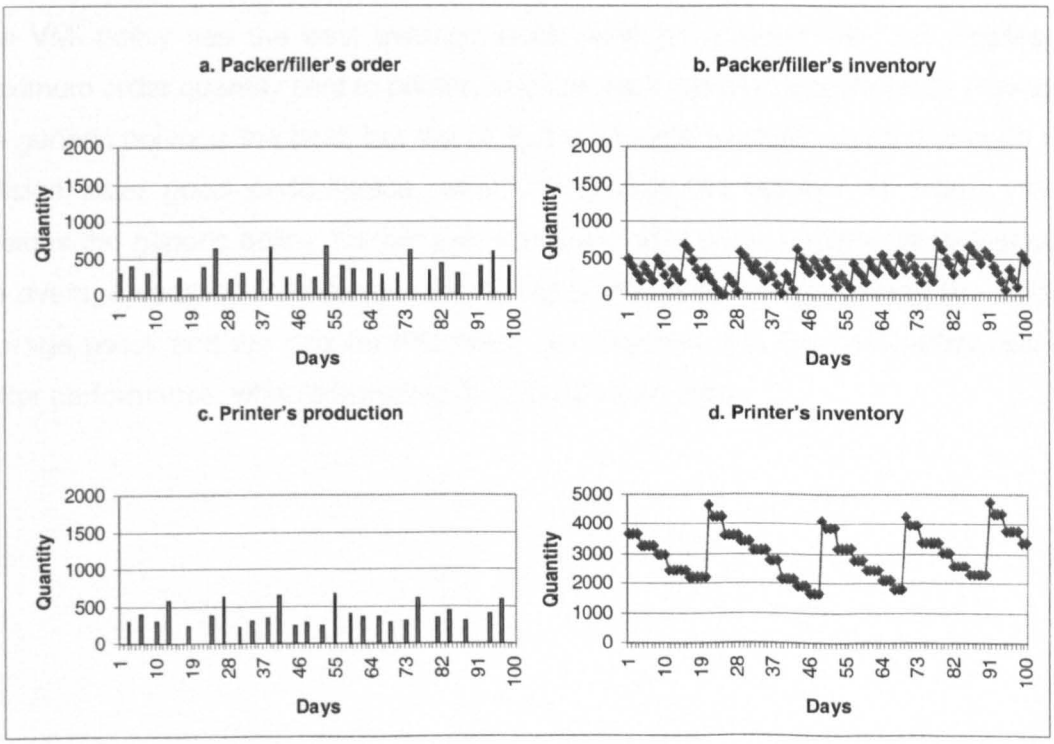



**Figure 5-7.** Production rates and inventory levels of the system with VMI policy (at printer) in response to a random change in retailer's demand.

A random change in the retailer's order that begins on *d*=9 causes the inventory level at company D, the packer/filler, to be within range. The weekly orders made are shown to be changing. In many instances, it shows how some emergency orders are being issued. This demonstrates the action of the inventory policy to regulate the stock level.

As depicted in Graphs *b, c*, and *d*, the random change in the retailer's order induces demand variations that are transmitted to company D. As depicted in graph *a,* in many instances, company D has to order more to meet demands (depending on the randomness of the demand from retailer). This effect is transmitted upstream to company C, who has to produce more, to meet the demands by the company downstream. Graph *c* shows the utilization of the printer production.

Table 5-7 gives the performance metrics (measures) achieved by the five order decisions (inventory policies). The system is subjected to a random demand pattern from retailer.

The VMI policy has the best average stock level (at packer/filler), the smallest in maximum order quantity sent to printer, and the least demand amplification. However, the generic policy is the best, but the (*s,S*), the smooth average and the pseudo PID policies have good performance, when comparing the number of orders made. Besides the generic policy, the smooth average policy gives a better performance in the average variation in order quantity set to printer. The generic policy, the smooth average policy and the pseudo PID policy are the best, but the (*s,S*) policy has the better performance, when comparing the risk of stock-outs.

**Table 5-7.** Comparison on the effectiveness of implementing the ordering decision (policy) based on the performance metrics.
(For each case, the system is subjected to a similar random input)

| Performance metrics | Order decision at packer/filler, $u_D$ | | | | |
|---|---|---|---|---|---|
| | **Test IV-a** *Generic* | **Test IV-b** *(s,S)* | **Test IV-c** *Smooth averaged* | **Test IV-d** *Pseudo PID* | **Test IV-e** *VMI* |
| Maximum and minimum stock levels at D (packer/filler) and C (printer). | | | | | |
| $I_{Dmax}$ | 930 | 1100 | 940 | 1270 | 730 |
| $I_{Dmin}$ | 100 | 0 | 110 | 70 | 0 |
| $I_{Cmax}$ | 4090 | 3990 | 3890 | 3870 | 4750 |
| $I_{Cmin}$ | 1050 | 1050 | 880 | 960 | 1660 |
| Average stock levels at D (packer/filler) $I_{Dav}$ and C (printer) $I_{Cav}$ | 505<br>2704 | 526<br>2892 | 530<br>2562 | 651<br>2671 | 346<br>3015 |
| Maximum order quantity to printer, $u_{Dmax}$. | 700 | 890 | 850 | 950 | 670 |
| Average variation in order quantity set to printer | 84 | 358 | 171 | 251 | 317 |
| Number of orders at day d | 16 | 17 | 17 | 17 | 28 |
| Number of emergency orders, *E* at day d | 1 | 3 | 2 | 2 | *NR* |
| Risk of stock out (use number of stock-outs per 100 days as measure). | 0 | 1 | 0 | 0 | 2 |
| Demand amplification | 158.24 | 145.64 | 171.66 | 160.6 | 92.06 |

*Note:*
*NR- not relevant, since no emergency order is generated.*

## 5.7 Results and analysis

A closer look at the data in Table 5-4, Table 5-5, Table 5-6, and Table 5-7 reveals that there are some data and performance measures that could draw meaningful comparisons between the policies. These are the average stock level, the average variation in order quantity set to printer, and the downstream demand amplification. In order to achieve these, the values (data) in Table 5-4, Table 5-5, Table 5-6 and Table 5-7 are first normalised. To normalise the values the highest average stock level, the

average variation in order quantity set to printer, and the downstream demand amplification have been taken as references, that is set to 1. A comparison of results in terms of the specified performance measures and the improvements over the generic policy is presented in Table 5-8.

It is interesting to note that each policy shows certain aspect of improvement over the generic policy.

- The (*s,S*) policy shows improvement in the average variation in order quantity set to printer, in response to a step demand pattern, and also in the downstream demand amplification, in response to a random demand pattern.
- The smooth average policy shows improvement in the average variation in order quantity set to printer, in response to a step demand pattern, and also in the downstream demand amplification, in response to a sinusoidal demand pattern.
- The pseudo PID policy shows improvement in the average variation in order quantity set to printer, in response to a step demand pattern.
- The VMI policy shows improvement in the average variation in order quantity set to printer, and also in the downstream demand amplification, in response to a step demand pattern. In response to a sinusoidal demand pattern as well as to a random demand pattern, the model implementing the VMI policy shows improvement in the average stock level (at packer/filler) and in the downstream demand amplification.

The smooth average policy is the best, but the pseudo PID has good performance, when comparing (indices) the average variation in order quantity set to printer, in response to a step demand pattern.

The VMI policy has the best performance indices in the average stock level (at packer/filler), and in the demand amplification, in response to a sinusoidal demand pattern as well as in response to a random demand pattern.

**Table 5-8** Average stock level, average variation in order quantity set to printer, and downstream demand amplification indices for generic, (*s,S*), smooth average, pseudo PID and VMI decision policies at packer/filler.

| **Performance metrics** | **Generic** | | | |
|---|---|---|---|---|
| | Retailer order pattern | | | |
| | Pulse | Step | Sine | Random |
| $I_{Dav}$ | | 0.5762 | 0.9568 | 0.7757 |
| $V_{Dav}$ | 0.0435 | 1.0000 | 0.0000 | 0.2346 |
| Var ($u_D$)/ Var ($u_E$) | | 0.5568 | 0.9173 | 0.9218 |
| **Performance metrics** | **(*s,S*)** | | | |
| | Retailer order pattern | | | |
| | Pulse | Step | Sine | Random |
| $I_{Dav}$ | | 1.0000 | 1.0000 | 0.8079 |
| $V_{Dav}$ | 0.913 | 0.6364 | 1.0000 | 1.0000 |
| Var ($u_D$)/ Var ($u_E$) | | 1.0000 | 1.0000 | 0.8484 |
| % improvement $I_{Dav}$ | | -42.38 | -4.32 | -3.22 |
| % improvement $V_{Dav}$ | -86.95 | ***+36.36*** | -100.00 | -76.54 |
| % improvement Var ($u_D$)/ Var ($u_E$) | | -44.32 | -8.27 | ***+7.34*** |
| **Performance metrics** | **Smooth average** | | | |
| | Retailer order pattern | | | |
| | Pulse | Step | Sine | Random |
| $I_{Dav}$ | | 0.7159 | 1.0000 | 0.8141 |
| $V_{Dav}$ | 0.3043 | 0.0909 | 0.2897 | 0.4776 |
| Var ($u_D$)/ Var ($u_E$) | | 0.9826 | 0.8978 | 1.0000 |
| % improvement $I_{Dav}$ | | -13.97 | -4.32 | -3.84 |
| % improvement $V_{Dav}$ | -26.08 | ***+90.91*** | -28.97 | -24.30 |
| % improvement Var ($u_D$)/ Var ($u_E$) | | -42.58 | ***+1.95*** | -7.82 |
| **Performance metrics** | **Pseudo PID** | | | |
| | Retailer order pattern | | | |
| | Pulse | Step | Sine | Random |
| $I_{Dav}$ | | 0.9703 | 0.9767 | 1.0000 |
| $V_{Dav}$ | 0.7348 | 0.3091 | 0.8589 | 0.7011 |
| Var ($u_D$)/ Var ($u_E$) | | 0.9944 | 0.9824 | 0.9356 |
| % improvement $I_{Dav}$ | | -39.41 | -1.99 | -22.43 |
| % improvement $V_{Dav}$ | -69.13 | ***+69.09*** | -85.89 | -46.65 |
| % improvement Var ($u_D$)/ Var ($u_E$) | | -43.76 | -6.51 | -1.38 |
| **Performance metrics** | **Vendor-managed inventory** | | | |
| | Retailer order pattern | | | |
| | Pulse | Step | Sine | Random |
| $I_{Dav}$ | | 0.7042 | 0.5631 | 0.5315 |
| $V_{Dav}$ | 1.000 | 0.9870 | 0.9278 | 0.8855 |
| Var ($u_D$)/ Var ($u_E$) | | 0.4529 | 0.4149 | 0.5363 |
| % improvement $I_{Dav}$ | | -12.80 | ***+39.37*** | ***+24.42*** |
| % improvement $V_{Dav}$ | -95.65 | ***+1.30*** | -92.78 | -65.09 |
| % improvement Var ($u_D$)/ Var ($u_E$) | | ***+10.39*** | ***+50.24*** | ***+38.55*** |

Notably, the printer company aims to achieve cost savings by having longer production run (in a large batch), at a fixed interval, and at less frequent productions. The packer/filler company aims to provide a more reliable service and lower prices and make a more accurate forecast.

Even though the results (Table 5-7) indicate that the generic policy has some performance measures better than the others, the tests were performed assuming for a non-growth situation. The main disadvantage of the generic policy is the fixed weekly order that does not consider forecasting, which can lead to poor regulation. For example if the retailer reduces orders for a substantial period of time (in the case for a long time of negative growth in retailer's order as shown in Figure 5-8) there will be an upward trend in the packer/filler's inventory. The cost of holding these extra stock will be substantial.

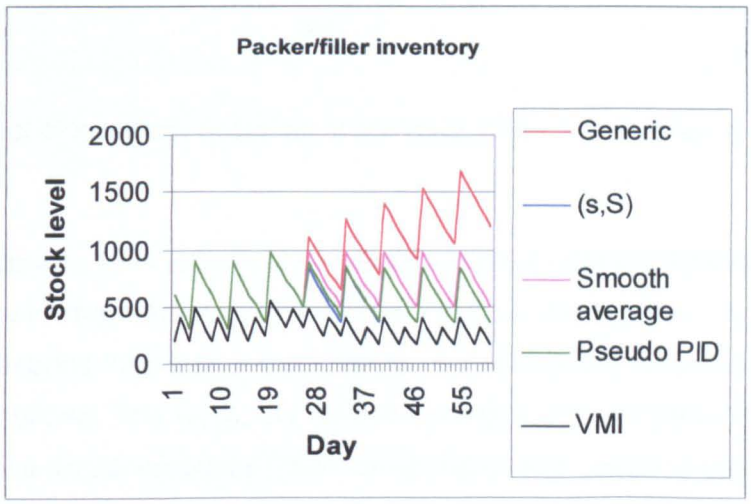



**Figure 5-8.** The effect of long period of negative growth in retailer's order on the Packer/filler's inventory.

Simulation for (*s,S*) policy, smooth average, pseudo PID and VMI show the future deliveries decreased to compensate for the order changes. However, this does not happen when applying the generic policy. The fact that for generic policy, the weekly order is assumed fixed to 700 units, (or, equivalent to seven days multiply with the nominal daily order, or 100 units, from retailer). The simulation does not show the decrease in future order (issued by packer/filler) to compensate for the order changes (demand from retailer).

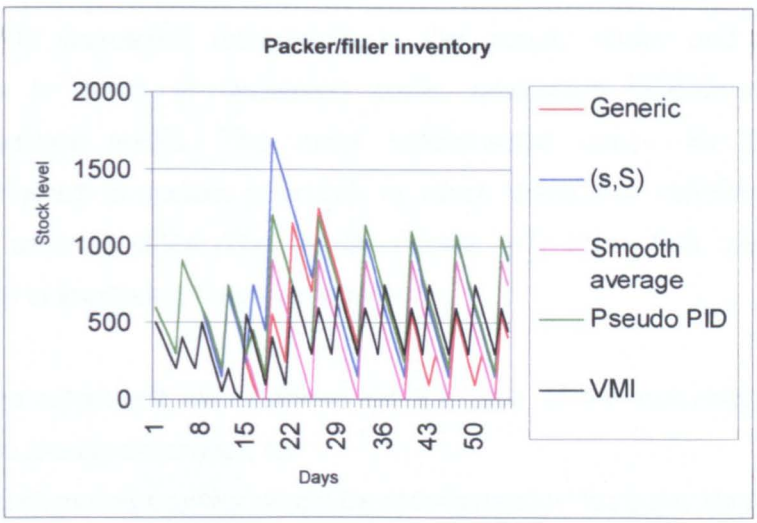



**Figure 5-9**. Effect of inventory policy on stock level at the packer/filler, to illustrate the response time.

Plots for the response time (speed of response) of each policy is illustrated in Figure 5-9. The response time measures how long it takes for the system ( in this case the stock level) to respond following a disturbance. The VMI policy responds much faster than the other policies. The (*s,S*), the smooth average and the pseudo PID policies are shown to have similar response times, while the generic policy is the slowest.

The main findings from the simulation are summarised as follows:

- The smooth average policy takes the least time to return to the steady state level. The response from the VMI policy and (*s,S*) policy in this respect is still within acceptable range.

- The VMI policy does respond much faster than the other policies, followed by the (*s,S*), the smooth average and the pseudo PID policies which have similar response times. The generic policy is the slowest.

- Simulation results show that VMI policy has the advantage of reducing the inventory levels, and the size of productions. However, the number of production runs increases. For VMI, the average order variations (in all tests) are relatively high based on the fact that the number of production runs (at printer) are higher

than all the other policies. Demand amplification, has been identified as contributing to increased uncertainty in the supply chain and hence poor performance in terms of increased costs, protracted lead-times and poor customer service levels. The main fundamental cause for the demand amplification effect is system structure, in which there is a combination of time delays and ordering rules. The results (Table 5-7) show that the VMI policy performs well in improving these variabilities.

- The policy to adopt will also depend on the type of the downstream demand patterns. The results show that, for
  a. The smooth average policy would be recommended for pulse demand pattern.
  b. The smooth average or the VMI policy would be recommended for step demand pattern.
  c. The VMI policy would be recommended for sine demand pattern.
  d. The VMI policy would be recommended for random demand pattern.

VMI is shown to reduce inventory levels by supplying smaller quantities (of variable sizes) at fixed intervals. However such small deliveries (due to shorter production) can often leads to larger set-up costs. A much lower inventory ($I_{Cav}$) at the printer would be expected if the value $Q_C$ in the ($s_C$,$Q_C$) policy (applied at the printer) is made smaller.

($s$,$S$) policy may show a poor performance but in terms of stability, this policy is based on forecasting (past data are analysed to establish the basic level of demand) and has the ability to adjust to retailer's ordering trend, even for a long time of positive growth or a long time of negative growth.

Pseudo PID policy in some aspects may not be that promising over the other policies. In terms of stability, this policy has the ability to adjust to retailer's ordering trend. This policy has the potential to show better results if further improvement to the gains were achieved. For example, other techniques such as gain scheduling could be incorporated in the inventory control model.

## 5.8 Summary

With the aid of the ARENA model, many aspects of the supply chain has been analysed and understood. As a decision support system (DSS), this model allows the decision-maker at company D specifically to analyse the consequences of decisions, and determine potential solutions to problems, and also propose alternative policies that may achieve some combination of low cost and high customer service. Specifically, it may be used to simulate the important decision which affects production/ordering, and to test the effect of different decision policies, on the system performance. If the decision-maker can understand the supply chain dynamics and its variability behaviour, and make changes to the supply chain based on this understanding, better performance from the supply chain can be expected.

However, this chapter so far has been limited to analysing the effect of changing the retailer's demand on the other parameters in the model. The next chapter will address several issues such as the ability of the system to adjust to more complex disturbance signals.

# Chapter 6

# Contextual load model

## 6.1 Introduction

Supply chain management is managing the flow of materials and products from the source to the user. As has been mentioned in Chapter 2, this flow typically includes aspects of purchasing, manufacturing, capacity planning, operations management, production scheduling, manufacturing requirements planning, distribution system planning, transportation systems, warehousing and inventory systems, and demand input from sales and marketing activities. Due to the complexities of the supply chain system where different stages in the system may have different conflicting goals and objectives, the ability to analyse and understand the many aspects of the supply chain system is important for effective decision-making. This chapter continues the modelling task that has been developed in the previous chapters to answer a key question: what will be the dynamic behaviour of a particular parameter (example, the inventory level) in response to a change of a disturbance parameter value (example delay in delivery) at a different location in the system? The focus will be to study the effectiveness of the controller (decision policies) to provide stability under the presence of disturbances, as well as evaluating the effect of disturbances on the process (the supply chain system).

The model described so far assumed that the input to the system originated from a single source. In the model, the demand has been calculated from the requirements downstream: it originates from the daily order issued by the retailer.

As a decision-support system (DSS), the model allows a decision-maker (manager) in company D to analyse the consequences of the policy of interest (by specifying the ordering policy, $u_D$). Although the simulation results provide some new insights about the behaviour of the system, the results obtained so far may not reveal the complex behaviour of supply chains. Throughout the experiments, it is assumed that the production facilities and the transportation systems are working under no-disturbance conditions. Given this view, the performance measures that show adaptability are the ones that have been chosen, for example, in the presence of disturbance in the production lines (manufacturing), and in market conditions. The need to model the supply chain more realistically requires that some additional design requirements be introduced. There are various situations that could be addressed, but in this work, some of the questions to which answered are sought, are as follows:

- Will the system be able to adjust to *changes in product demand?*
  - For example in situations where the lower echelon reduces orders, or increases orders.
- Will the system be able to adjust to changes in *manufacturing capacity*?
  - For example in situations of machine breakdown.
- Will the system be able to adjust to *inventory disturbances*?
  - For example in situations where supplier provides incorrect amount of material.

Such an extended realistic model can be viewed as consisting of the supply chain model, made up of several components, together with its contextual components. These components are dynamic and are characterised by several variables, each changing with events and each linked through events to other variables. Each of the particular situations of interest represents one contextual component of the complex system (the supply chain). Meaningful analysis for revealing the complex behaviour of the supply chain system must consider modelling the system and its relation to its contextual components, that is, how the supply chain system would react to its environment. Accordingly, the answer to this issue can be addressed through contextual load modelling.

## 6.2 Contextual load model design

The *contextual load* modelling is conducted in this work with the realisation that meaningful investigation of a particular system, in this case the supply chain system, indeed can be achieved by explicitly accounting for its environment. The task of developing the *contextual load* model would require the identification of the possible sources of disturbances that might exist in the system, the modelling of these disturbances and to decide the particular parameters in the model that is to be changed to simulate such disturbances. With this view, it is necessary to develop a general conceptual framework towards implementing a systematic and efficient representation of the contextual load model.

Figure 6-1 illustrates a general conceptual framework for the supply chain system. The orders (messages) can be regarded as feedback signals. The inventory (stock levels) is regarded as the controlled variable, CV. The measured value of the CV is transmitted to the feedback controller (decision-maker), and this controller makes a decision on the quantity to order or to be issued to the upper stage (echelon) based on the ordering policy (rules).

The feedback controller (decision-maker) calculates the required amount to order based on the stock level, PV, and the ordering policy (rules). This value is reflected as the needed values of the manipulated variables, MV. The process represents the physical changes of the entities, for example, the process of transforming blank labels into printed labels, etc. Disturbance is any undesired change that takes place in a process which tends to affect adversely the values of the CVs, the input or the process.

The general conceptual framework for this system, as shown in Figure 6-1, needs to be expanded to more closely represent the inter relations of the variables, CVs, MVs, and PVs, and the processes that exists in the supply chain system. Such a functional layout, showing the detailed behaviour of the system including the disturbances mentioned in Figure 6-1, is illustrated in Figure 6-2.

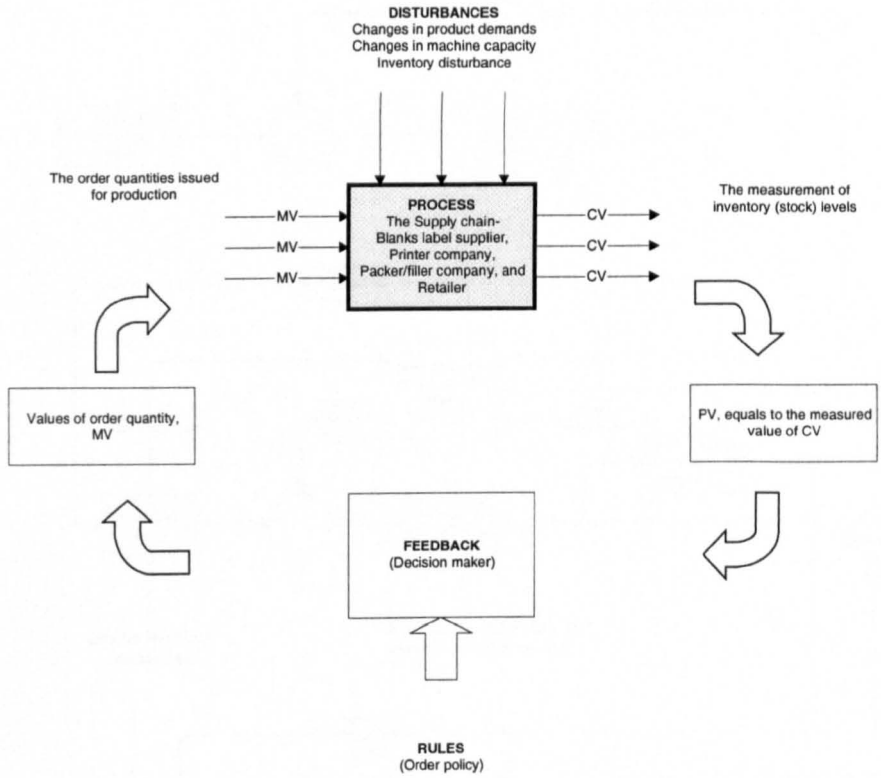



**Figure 6-1** General conceptual framework for the supply chain system.

On receiving an order from the lower echelon (retailer), the decision-maker at the packer/filler company will decide on when to start production, and at a specific time of the day will issue this information, as a MV (shows as $MV_D$) to the packer/filler production. Also, at some specified time of the day, the printed labels stock level is read. This information is used by the decision maker at the packer/filler company to decide on the size to order, the time to place an order, and perform the ordering. This is shown as $u_D$, or $PV_C$. This information is later used to calculate the required $MV_C$. Hence, the decision-maker at the packer/filler company is analogous to a feedback controller that performs the control of issuing orders and production, and regulates the stock level.

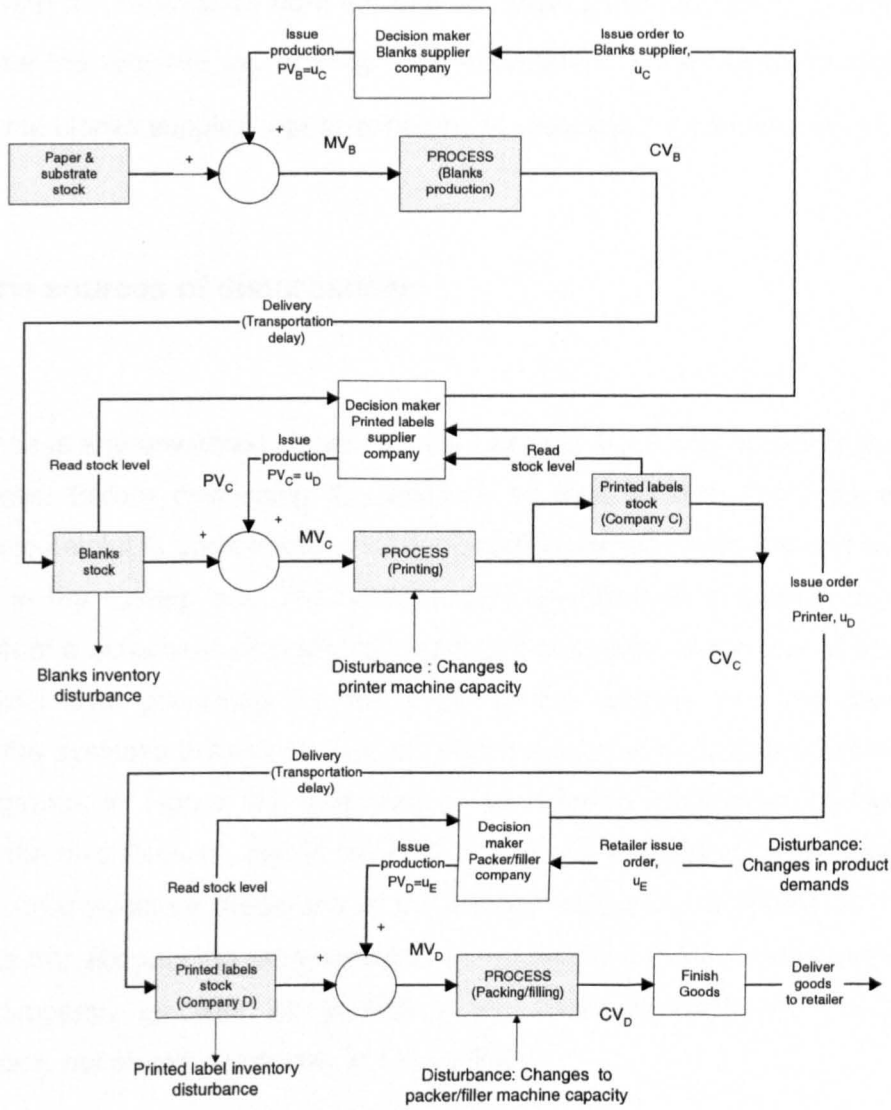



**Figure 6-2** Functional layout of a packaging industry supply chain

The same analogy also applies to the decision maker at the printer company. On receiving an order, $u_D$, from the lower echelon (packer/filler), the decision maker at the printer company will decide on when to start production, and at a specific time of the day will issue this information, as a MV (shows as $MV_C$) to the printer production.

Also, at some point in time, the blanks labels stock level is read. This information together with the information from the printed labels stock (company C) is later used to calculate the required $u_C$, or $PV_B$. This information is then used by the decision maker at the blanks supplier (upper echelon), to calculate the required $MV_B$.

## 6.3 The sources of disturbances

Disturbance is any unwanted signal that corrupts the input and output of the plant or the process. Before discussing the sources of disturbances that may affect the system, it is helpful to understand what the possible disturbances are and where their locations in the system are. The analysis and identification sequence involves the production of a schematic diagram highlighting the physical behaviour of the system, the physical laws governing the behaviour of the system, and the disturbances affecting the system's behaviour. The functional layout of the system represented as block diagrams in Figure 6-2 that shows the detailed description of the system, including the disturbances, allows the next phase of the analysis to be conducted. A control system structure presented in a schematic diagram as shown in Figure 6-3 would take into account the representation of the decision-makers (at packer/filler and printer company) as well as providing the exact locations of the assumed disturbances, not shown previously in Figure 6-2.

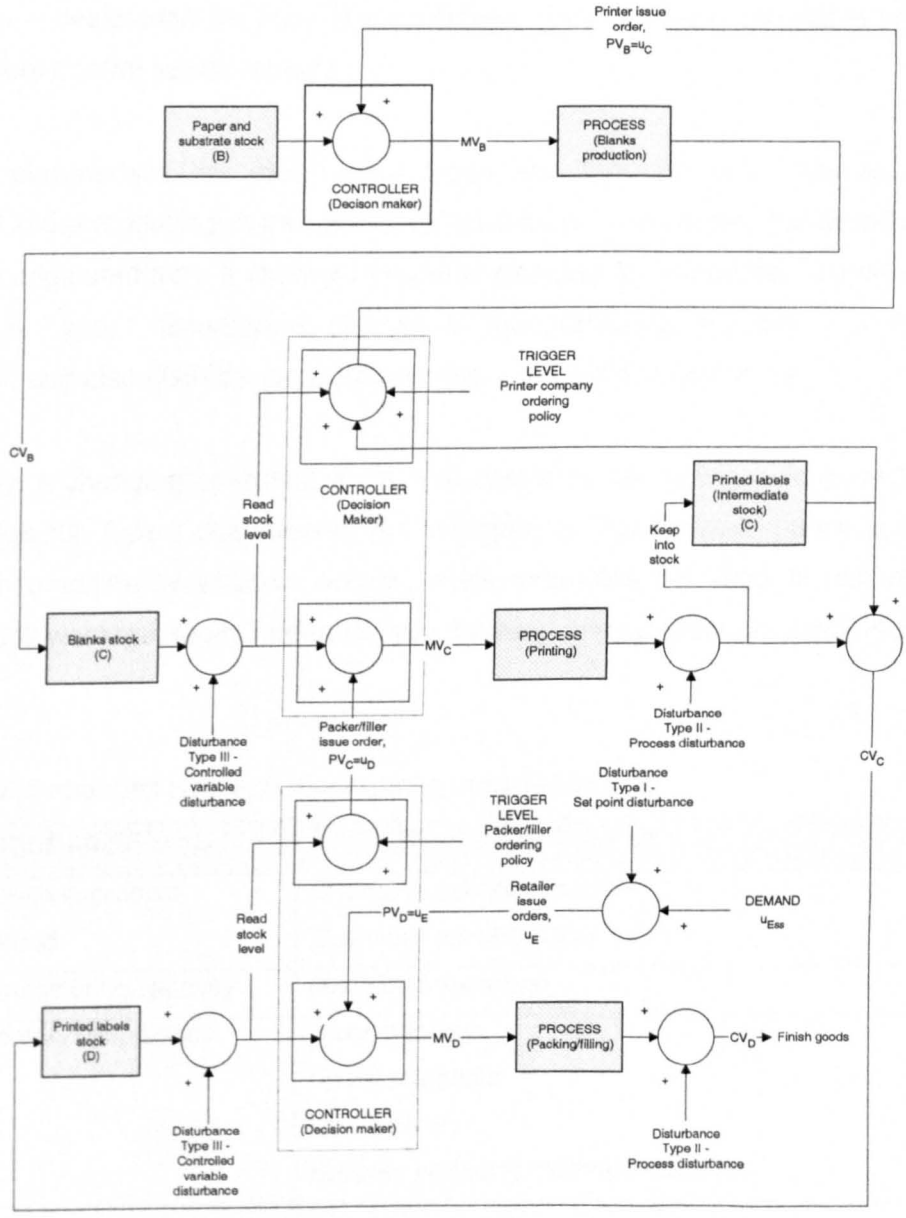



**Figure 6-3** The control system structure of the packaging industry supply chain system.

The schematic diagram of the system as depicted in Figure 6-3 underlies the identification of the disturbance types that may be present, namely: (a) The set-point (input) disturbance – designated as Type I disturbance, (b) The process (plant)

disturbance – designated as Type II disturbance, and (c) The control variable (output) disturbance – designated as Type III disturbance. This selection correlates with the concepts from control system theory.

Table 6-1 summarises the disturbance types and their possible sources to be considered in the modelling of the contextual load model. As shown, the disturbances could have originated from a change in product demand (or variations of orders from retailer) – a Type I disturbance, change in manufacturing capacity – a Type II disturbance, and also disturbance to inventories – a Type III disturbance.

In this study, a changing operating point, and customer cancelling orders are two of the examples for Type I disturbance. An example for Type II disturbance is in the event when machine breakdown occurs, while examples for Type III disturbance includes stock wastage, faulty materials, late delivery, and supplier providing incorrect material.

**Table 6-1** Disturbances type and the sources of disturbances.

| Type | Disturbance | Sources of disturbances |
|---|---|---|
| I | Change in product demand | Changing operating points<br>Customer cancel orders |
| II | Manufacturing capacity | Machine breakdown |
| III | Inventory disturbance | Stock wastage<br>Faulty materials<br>Late delivery<br>Supplier providing incorrect material. |

## 6.4 Modelling the disturbances

The objective for this part of the research are to assess the effectiveness of each ordering policy in adjusting to changes in product demand, changes in manufacturing capacity, and inventory disturbances.

The next task in developing a contextual model would require an understanding on how to model these disturbances and to decide on what particular parameter(s) in the model to be changed to simulate such a particular disturbance.

### 6.4.1 Type I disturbance: Change in product demands

- *Changing in operating points:*
  A variation in ordering pattern from the retailer will represent changes in product demands. For example, modelling this disturbance on the packer/filler company requires the model components to simulate an occasional change in the order quantity of retailer deviating from that of the usual demand due to product promotions and/or seasonal and trend factors.

- *Customer cancelling orders:*
  The modelling of a cancellation of order is achieved by making the order quantity from retailer to drop to zero for that particular day.

### 6.4.2 Type II disturbance: Manufacturing capacity disturbance

- *Machine breakdown at printer:*

  Breakdowns can have a major effect on the performance of manufacturing systems. Many authors have discussed the proper modelling of breakdown (or downtime) data. These have been extensively discussed in [Williams 94], [Clark 94], [Law and Kelton 91]. Breakdowns or failures can be deterministic or probabilistic in duration. Scheduled maintenance, for example, changes of fluids every three months when a complete lubrication is required, can be classified as deterministic. The breakdown is classified as probabilistic for almost all other circumstances. However, this requires either actual data for choosing a statistical distribution, or a reasonable assumption when data is lacking based on the physical nature of causes of downtimes.

In this study, two cases will be considered: (a) breakdown occurs before a regular order was made, and (b) breakdown occurs after a regular order was made. To effectively simulate these two cases, the modeller/programmer should have the flexibility to choose the point of time to create the breakdown and also the duration of the breakdown. The following assumption is made regarding its implementation: Failure is modelled to take place immediately upon the occurrence of a breakdown. Once the machine has been repaired it will continue processing the order that was interrupted when breakdown occurred, until completion. Any order that was received during the breakdown period will not be processed.

### 6.4.3 Type III disturbance: Inventory disturbance

- *Faulty materials in printer:*

  It is assumed that some portions of the material are damaged during the printing processes when this disturbance is present. This disturbance is modelled by treating that when packer/filler (company D) make an order of $q$ units, the printer (company C) will print the amount as ordered. The production at printer will be $q$ units, but due to faulty material the quantity delivered to packer/filler will be $q$ units less the faulty.

- *Late delivery:*

  This disturbance arises due to an unnecessary delay in the delivery of goods from printer company to packer/filler company. For example, late delivery may happen a few times during a certain period of time. The modelling of this disturbance is achieved by using a pure time delay block between the printer and the packer/filler.

- *Stock wastage in packer/filler:*

  It is assumed that there are some percentage of material being damaged during transportation, or that material is scrapped due to changes in design format in the presence of this disturbance. In terms of disturbances, this would be reflected as an inventory disturbance, whose modelling has been discussed earlier in modelling the faulty material disturbance.

- *Supplier providing incorrect material:*
  This disturbance assumes that the supplier provides material that is not the same as that ordered. For the system, it would be reflected as an inventory disturbance, and can be modelled as in modelling the faulty material disturbance. However, the magnitude in this case would be large in comparison to the faulty material disturbance.

Table 6-2 summarises the requirements for modelling these disturbances, and specifies the particular parameter to be considered in each model. Column 1 lists the type of disturbances, column 2 lists the disturbances to be modelled, and column 3 describes the method of implementing these disturbances.

**Table 6-2**. Models for the simulation of disturbances.

| Sources of disturbances | Modelling disturbances | Implementation |
|---|---|---|
| Type I<br>Change in product demand | a. Changing in operating point. | Varying retailer's ordering pattern |
| | b. Customer cancelling order. | Retailer's order set to zero |
| Type II<br>Manufacturing Capacity | a. Machine breakdown | Breakdown is modelled to happen immediately on the occurrence of a breakdown. Once the machine is repaired it will continue to process the order until completion. |
| Type III<br>Inventory disturbance | a. Faulty material. | Quantity delivered equals *q* units minus the faulty. |
| | b. Late delivery. | Modelling using the time delay block. Assuming packer/filler's order of *y* units is delivered 96 hours late. |
| | c. Stock wastage, example the stock becoming useless (changes in label's design format, etc). | Similar to modelling faulty material. |
| | d. Supplier providing incorrect material. | Similar to modelling faulty material. |

The creation of the relevant routines for the modelling will be addressed in section 6.5. In section 6.6 the contextual model is utilised for several tests of "what-if" scenarios in the presence of disturbances. The purpose is to investigate how the various disturbances affect the behaviour of the supply chain system controlled by the inventory policies presented in chapter 5, and to give a qualitative characterisation of their performances.

## 6.5 Modelling disturbance routines

As discussed in section 3.2 of chapter 3, some DES languages such as SIMAN, ARENA, and SIMSCRIPT have both process-oriented and event scheduling schemes capabilities. It is important to note that the event scheduling scheme capability would allow the programmer to control the logic flow (including the occurrences of events) in the simulation model. If the programmer has the flexibility to control the logic and events flow, then the implementation of disturbances could be realised by creating the appropriate routines. The approach to be described here is devised to create the DES routines for the modelling of the disturbances.

In order to implement the disturbances as specified in Table 6-2, the following steps have been taken.

a. Define a set of events at each particular resource. The resources refer to the inventories and production machines of interest.
b. Define a set of states for each resource.
c. Draw a DES sample path (a timing diagram with arrows with events denoted by arrows at the times they occur). A sample path can only jump from one state to another whenever an event occurs.
d. Indicate on the DES sample path the state at which the system would be, upon the occurrences of a particular disturbance. By using DES sample path to capture the characteristics of the resource, the desired behaviour of the resource when an unexpected disturbance occurs could be observed and understood.
e. Give a written implementation on DES, of modelling the particular disturbance.
f. Utilise ARENA modelling tools (modules) to implement the routines.

The DES sample paths developed in the modelling of the disturbances as listed in column 2 of Figure 6-4 are as follows:

- Varying retailer's ordering patterns:

Define the set of events for the ordering as $E_{R\ order}$ = { Issue order equals $Q_{nom}$ , Issue order above $Q_{nom}$ , Issue order below $Q_{nom}$ }

where,

Issue order equals $Q_{nom}$ denotes the ordering of $Q_{nom}$ , [$e_1$ in Figure 6-4]

Issue order above $Q_{nom}$ denotes the ordering of above $Q_{nom}$, [$e_2$ in Figure 6-4]

Issue order below $Q_{nom}$ denotes the ordering of below $Q_{nom}$ , [$e_3$ in Figure 6-4].

Define the set of states for the retailer's as $X_{R\ order}$ = { $Q_{nom}$ , Above $Q_{nom}$ , Below $Q_{nom}$ }

where,

$Q_{nom}$ denotes the nominal quantity being ordered by the retailer , [$x_1$ in Figure 6-4]

Above $Q_{nom}$ denotes the quantity being ordered by the retailer is above nominal , [$x_2$ in Figure 6-4]

Below $Q_{nom}$ denotes the quantity being ordered by the retailer is below nominal , [$x_3$ in Figure 6-4].

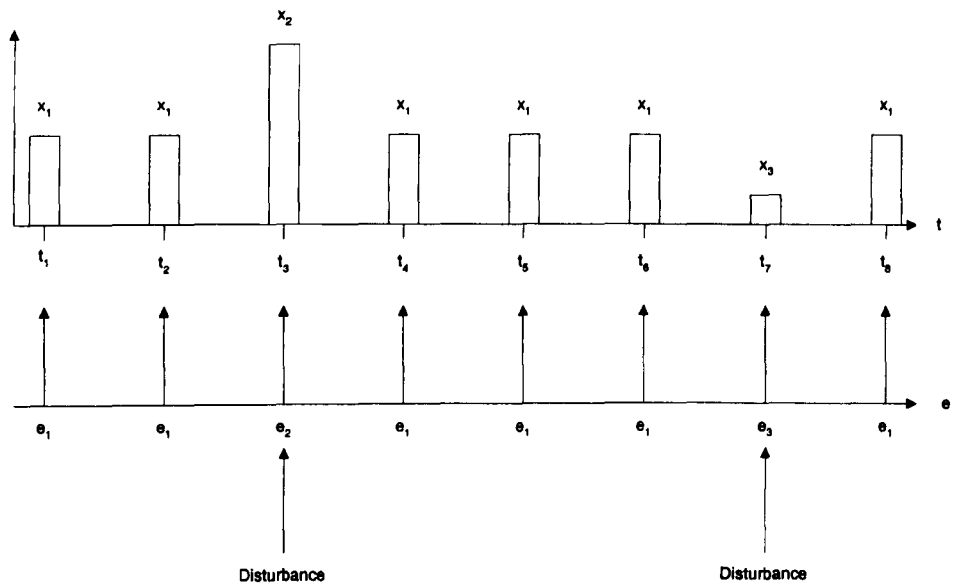



**Figure 6-4** Sample paths for retailer's ordering pattern

Figure 6-4 shows the sample paths for retailer's ordering pattern. The system would be modelled to behave as follows: Whenever $e_1$ occurs, the state of the order would be $x_1$ . This can be thought of as the system being in its steady state. For the case of disturbances, the state would be $x_2$ when $e_2$ is triggered, and if $e_3$ is triggered the state would be $x_3$. The triggering of event $e_2$ or $e_3$ would cause the ordering pattern to deviate away from the nominal values.

The routine for creating the retailer's ordering pattern would be as follows:

During no-disturbance, $e_1$, the state $x_1 = k * x_1$, where k=1

Upon the occurrence of a disturbance, $e_2$, the state $x_2 = k * x_1$, where $k > 1$

Upon the occurrence of a disturbance, $e_3$, the state $x_3 = k * x_1$, where $k < 1$

Example: The nominal order quantity is 100 units, hence for k=1 (during no-disturbance), the order is 100 units. To create a Type I disturbance (changing operating points) the value k is adjusted, say k=1.3, the order is 130 units, and if say k=0.8, the order is 80 units.

- Modelling machine breakdown.

Define the event set for the machine as

$E_{machine} = \{ arr_{mach}, dep_{mach} \}$

where

$arr_{mach}$ denotes an arrival of materials for production, [$e_1$ in Figure 6-5]

$dep_{mach}$ denotes a departure of goods from machine, [$e_2$ in Figure 6-5].

Define the state for the machine as

$X_{machine} = \{ B, I, D \}$

where

B denotes that the machine is in the busy state, [$x_1$ in Figure 6-5]

I denotes that the machine is in the idle state, [$x_2$ in Figure 6-5]

D denotes that the machine is in the down (failure) state, [$x_3$ in Figure 6-5].

A DES sample path for this system is as shown in Figure 6-5.

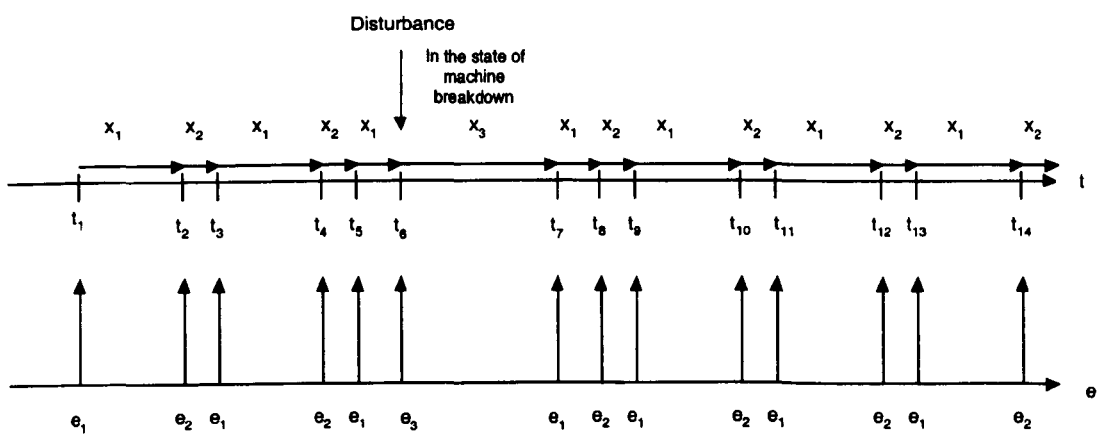



**Figure 6-5** Sample paths for machine breakdown.

The behaviour of the system would be as follows: Whenever $e_1$ occurs, the state of the resource would be $x_1$ (between $t_1$ and $t_2$ time interval). The state of the resource would be $x_2$ (between $t_2$ and $t_3$ time interval) when $e_2$ is triggered.

Modelling this disturbance will amount to initiating event $e_3$ followed by the event $e_1$ after the time duration of machine breakdown. Upon the occurrences of a disturbance (the point of time when $e_3$ is triggered), as shown to be at $t_6$, the state of the packer/filler machine would then be $x_3$ (between $t_6$ and $t_7$ time interval).

Example: The modeller/programmer has the flexibility to create the occurrences of $e_3$ . Say, $e_3$ occurs a day after a weekly order is issued, and the duration of the breakdown (the duration of time between $t_6$ and $t_7$) can be assigned as 3 days or 72 hours.

- Modelling faulty material.

Define the event set for the printer production as

$E_{Printer}$ production = {*No faulty, With faulty*}

where

*No faulty* denotes the production batch is 100% acceptable, [$e_1$ in Figure 6-6]

*With faulty* denotes the production batch is with faulty, [$e_2$ in Figure 6-6].

The state of the printer production can be written as

$X_P$ = { *q* , *q less faulty* }

where

*q* denotes the production batch of printed labels (from printer company), [$x_1$ in Figure 6-6]

*q less faulty* denotes the production batch with faulty labels, [$x_2$ in Figure 6-6].

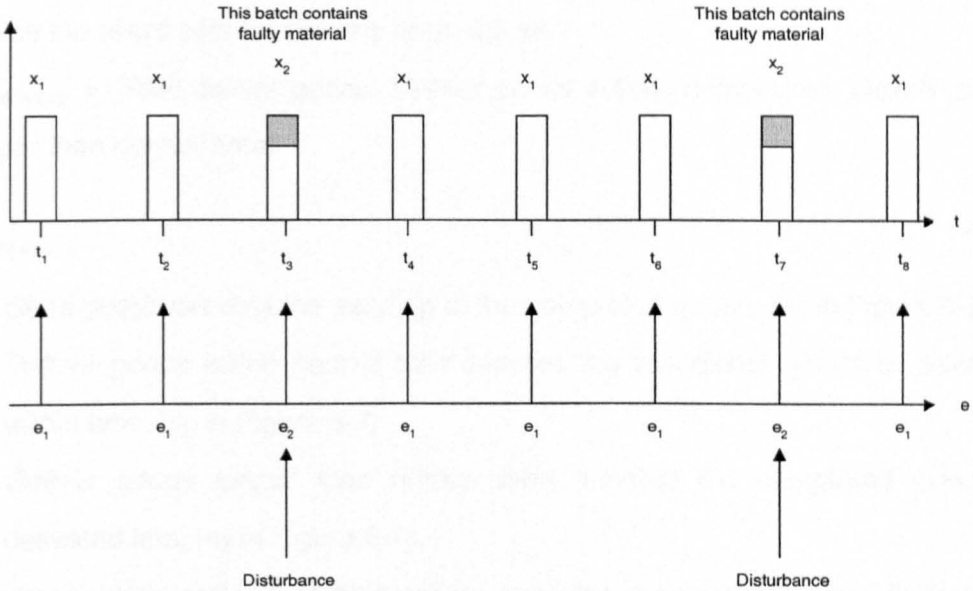



**Figure 6-6** Sample paths for packer/filler printed labels stock

The sample path is as shown in Figure 6-6. The behaviour of the system should be as follows: Whenever $e_1$ occurs, the state of the resource (printer production) would be $x_1$. For the case when $e_2$ is triggered, the state would be $x_2$ where the shaded region indicates the portion of the production is faulty.

The routine for creating this disturbance would be as follows:
Upon the occurrence of a disturbance, the production at printer will be *q* units, but due to faulty material, the quantity delivered to packer/filler will be *q* units less the faulty.
Example: The modeller/programmer has the flexibility to create the occurrences of event $e_2$. For example, $e_2$ occurs and the batch being produced is assumed to have faulty material (assigned with a % faulty, say $\alpha$). Upon completion, a portion that is assigned as faulty is disposed, and the other portion $(1-\alpha) * q$ is delivered to the next facility (company).

- Modelling late delivery.

Define the event sets for delivery of goods as

$E_{delivery}$ = {*Start deliver goods, Deliver goods within normal time, Deliver goods longer than normal time*}

where,

*Send goods* denotes the sending of the completed goods, [$e_1$ in Figure 6-7]

*Deliver goods within normal time* denotes the completed goods is delivered within time, [$e_2$ in Figure 6-7]

*Deliver goods longer than normal time* denotes the completed goods is delivered late, [$e_3$ in Figure 6-7].

[Any goods delivered in less time will be considered as within normal time, since the range of time is still within the specified 3 days period and could not adversely affect the parameters being measured].

The states of the receiver (inventory) can be written as follows:

$X_{receiver}$ { *Receive goods on time, Receive goods late* }

where,

*Receive goods on time* denotes the completed goods arrives within normal time, [$x_1$ in Figure 6-7]

*Receive goods late* denotes the completed goods arrives late, [$x_2$ in Figure 6-7].

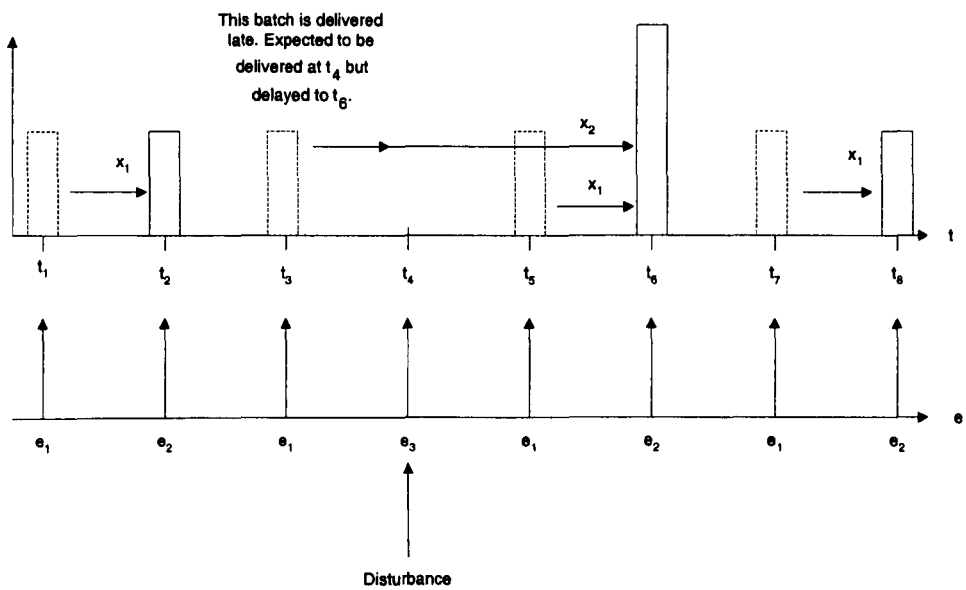



**Figure 6-7** Sample paths for late delivery

The sample path is as shown in Figure 6-7. As an illustration, the behaviour of the system should be as follows: When $e_1$ occurs, the printer production will send the completed batch of goods to packer/filler. For normal delivery (event $e_2$), the goods will be received at the indicated time. For late delivery (event $e_3$), the goods will be subjected to additional delay time, $t_{delay}$. For normal delivery $t_{delay}$ =0 hours. For late delivery $t_{delay}$ = {24 (for 1 day delay), 48 (2 days delay), 72 (for 3 days delay), etc.}.

The routine for creating this disturbance would be to use a delay block between printer production and packer/filler inventory, where during normal delivery this delay would be zero (no delay), and positive non-zero otherwise (with delay).

## 6.6 Simulation results and analysis

The following is a continuation in the modelling and simulation of the FMCG supply chain system. In Chapter 5, various "what-if" scenarios have been examined and analysed against different policies. This part of the work will address several "what-if" scenarios in the presence of disturbances.

The number of possible scenarios are combinatorial in terms of possible disturbances and hence not all would be tested. Likewise, there are various types of inventory policies that could be tested, see Silver *et.al.* [SilverPP 98]. However, the investigation in this work will be focussing on the same inventory policies analysed and discussed in Chapter 5.

### 6.6.1 Simulation example 1: Type I disturbance - Changes in product demand

The simulation for Type I disturbance is similar to the experimental work that has been presented in Chapter 5. This section discusses further tests conducted to understand the consequences when those parameters that might be open to change in the future, particularly when the input patterns (retailer demand) were varied. The simulation presented here focuses on the pulse type of various magnitudes in the product demand from retailer, with the steps of the pulse being varied to +20%, +40% , +60%, +80%, and +100% of the normal demand (100 units per day). To compare the effectiveness of each policy in the presence of variations in the input pattern, four different order policies (inventory policies) were considered and the results were tabulated in Table 6-3.

**Table 6-3.** Comparison on the effectiveness of the decision (policy) in the presence of variations in the input pattern, based on the performance metrics.

| | | Order decision at packer/filler, $u_D$ | | | |
|---|---|---|---|---|---|
| **Input** (Pulse demand pattern from retailer) | **Output Performance** | **Test PD-1a** *(s,S)* | **Test PD-1b** *Smooth averaged* | **Test PD-1c** *Pseudo PID* | **Test PD-1d** *VMI* |
| *120 units (+20% demand)* | *Stock levels at packer/filler:* | | | | |
| | $I_{Dmax}$ | 1040 | 900 | 990 | 560 |
| | $I_{Dmin}$ | 160 | 160 | 200 | 80 |
| | *Risk of stock-out* | 0 | 0 | 0 | 0 |
| *140 units (+40% demand)* | *Stock levels at packer/filler:* | | | | |
| | $I_{Dmax}$ | 1120 | 900 | 1080 | 620 |
| | $I_{Dmin}$ | 20 | 20 | 100 | 0 |
| | *Risk of stock-out* | 0 | 0 | 0 | 1 |
| *160 units (+60% demand)* | *Stock levels at packer/filler:* | | | | |
| | $I_{Dmax}$ | 1380 | 1020 | 1170 | 680 |
| | $I_{Dmin}$ | 120 | 0 | 0 | 0 |
| | *Risk of stock-out* | 0 | 1 | 1 | 2 |
| *180 units (+80% demand)* | *Stock levels at packer/filler:* | | | | |
| | $I_{Dmax}$ | 1460 | 1160 | 1320 | 880 |
| | $I_{Dmin}$ | 60 | 0 | 0 | 0 |
| | *Risk of stock-out* | 0 | 1 | 1 | 3 |
| *200 units (+100% demand)* | *Stock levels at packer/filler:* | | | | |
| | $I_{Dmax}$ | 1600 | 1400 | 1500 | 1100 |
| | $I_{Dmin}$ | 0 | 0 | 0 | 0 |
| | *Risk of stock-out* | 2 | 2 | 2 | 3 |

The (*s,S*) policy (test PD-1a) is able to keep the number of risks down to zero, for most cases (pulse size 120 ~ 180). For the smooth average and pseudo PID policies (test PD-1b and PD-1c), the risks start to occur earlier (for pulse size 160 ~ 200). For the VMI policy (test PD-1d), the risks start to occur even more earlier (for pulse size 140 ~ 200). However, the (*s,S*) policy forces the packer/filler to keep comparatively large stocks: implying that having larger stock reduces the risk of stock-out.

The results imply that the (*s*,*S*) policy is the most robust in keeping the risk of stock-out low if disturbances are in the form of larger product demand period. The smooth average policy is next best as well as the pseudo PID policy. The VMI is not robust, since the risk of stock-out increases with larger demand from the retailer.

### 6.6.2 Simulation example 2: Type II disturbance - Manufacturing capacity

The work presented here focuses on uncertainties during the occurrences of machine breakdown. Several performance metrics will be considered in making a comparison on the effectiveness of the different order decisions (inventory policies) at the packer/filler.

A decision-maker may want to know how these figures (performance metrics) change if the day of the breakdown is different. Specifically, the simulation will consider two cases: (a) breakdown occurs before the regular order is made (the effect of ignoring the regular order), and (b) breakdown occurs after regular order has been issued (if regular order is processed). In all tests, the model was subjected to the same test conditions: simulation time of 60 days, machine breakdown period of 4 days (96 hours), and assuming a smooth demand from retailer (100 units per day). Performance results for the first case are displayed in Table 6-4a, and for the second case in Table 6-4b.

**Table 6-4a.** Comparison on the effectiveness of the decision (policy) in the presence of disturbance (machine breakdown occurs before regular order is made), based on the performance metrics.

| Performance metrics | Order decision at packer/filler, $u_D$ | | | | |
|---|---|---|---|---|---|
| | **Test MB-1a** *Generic* | **Test MB-1b** *(s,S)* | **Test MB-1c** *Smooth averaged* | **Test MB-1d** *Pseudo PID* | **Test MB-1e** *VMI* |
| Time to return to steady state (in days) | 14 | 28 | 14 | 28 | 35 |
| Average stock levels | | | | | |
| at D $I_{Dav}$ ,and | 395 | 655 | 395 | 515 | 368 |
| at C $I_{Cav}$ | 2928 | 2768 | 2928 | 2796 | 3086 |
| Average variation in order quantity set to printer | 60 | 160 | 60 | 94 | 150 |
| Number of emergency orders, E at day *d* | 1 | 1 | 1 | 1 | *NR* |
| Risk of stock out . | 2 | 2 | 2 | 2 | 3 |
| Number of order batch undelivered | 1 | 1 | 1 | 1 | 2 |

*Note:*
*NR- not relevant, since no emergency order is generated.*

**Table 6-4b.** Comparison on the effectiveness of the decision (policy) in the presence of disturbance (machine breakdown occur after regular order is made), based on the performance metrics.

| Performance metrics | Order decision at packer/filler, $u_D$ | | | | |
|---|---|---|---|---|---|
| | **Test MB-2a** *Generic* | **Test MB-2b** *(s,S)* | **Test MB-2c** *Smooth averaged* | **Test MB-2d** *Pseudo PID* | **Test MB-2e** *VMI* |
| Time to return to steady state (in days) | 14 | 28 | 14 | 49 | 14 |
| Average stock levels | | | | | |
| at D $I_{Dav}$ ,and | 620 | 655 | 620 | 615 | 293 |
| at C $I_{Cav}$ | 2637 | 2632 | 2637 | 2647 | 2779 |
| Average variation in order quantity set to printer | 0 | 160 | 100 | 99 | 210 |
| Number of emergency orders, E | 0 | 1 | 1 | 1 | *NR* |
| Risk of stock out . | 2 | 2 | 2 | 2 | 4 |
| Number of order batch undelivered | 1 | 1 | 1 | 1 | 1 |

*Note:*
*NR- not relevant, since no emergency order is generated.*

One can see that the tests for (*s,S*) policy ( see Test MB-1b and Test MB-2b) show a similar output performance, indicating that even though the system is experiencing two different disturbances of machine breakdown, the effect will be the same throughout. This could suggest that the (*s,S*) policy provides good regulation in maintaining the stock. Tests for the generic, the smooth average, and the pseudo PID show an increase in the average stock level of the packer/filler company, when a machine breakdown occurs after the regular order has been issued. On the other hand, the VMI shows a considerable decrease in the average stock level at the packer/filler, when subjected to a similar disturbance.

Note that the lead times for all the tests (Test MB-1a ~ Test MB-1e, and Test-MB-2a ~ Test MB-2e) are assumed to be the same. It is worth noting that if the lead times for VMI is shorter, the performance metrics, particularly the time to return to steady state, the risks of stock-outs, and the number of stock-outs will be expected to be smaller (further improved).

### 6.6.3 Simulation example 3: Type III disturbance - Inventory disturbances

In modelling this disturbance, the printer will print the amount as ordered, but the fault is modelled to take effect after the printing is completed. The argument is, if the printer production and delivery are kept separate, then this can be modelled more effectively. For the first part of the tests, 20% of the order being delivered to packer/filler from printer is assumed to be faulty. The second part of the tests consider the modelling of stochastic disturbance, that is the fault is assumed to be random.

#### 6.6.3.1 Type III-Faulty material: Part 1- 'One-off' situation

The tests (Test FM-1a ~ Test FM-1e) assumed 20 % of material delivered from printer to packer/filler is faulty. The interest is focused on how effective the control

schemes (inventory policies) are in regulating the system to the occurrence of the disturbance (faulty materials). The performance results are displayed in Table 6-5a.

**Table 6-5a.** Comparison on the effectiveness of the decision (policy) in the presence of disturbance (faulty materials), based on the performance metrics.

| Performance metrics | Order decision at packer/filler, $u_D$ | | | | |
|---|---|---|---|---|---|
| | **Test FM-1a** *Generic* | **Test FM-1b** *(s,S)* | **Test FM-1c** *Smooth averaged* | **Test FM-1d** *Pseudo PID* | **Test FM-1e** *VMI* |
| Time to return to steady state (in days) | 14 | 14 | 14 | 42 | 21 |
| Average stock levels at D $I_{Dav}$ ,and at C $I_{Cav}$ | 519<br>2734 | 557<br>2737 | 573<br>2817 | 546<br>2852 | 291<br>3013 |
| Average variation in order quantity set to printer | 86 | 30 | 16 | 8 | 226 |
| Number of emergency orders, E at day *d* | 1 | 0 | 0 | 0 | *NR* |
| Risk of stock out . | 0 | 0 | 0 | 0 | 1 |

*Note:*
*NR- not relevant since no emergency orders were generated. For* VMI, the printer is sending goods (printed labels) twice a week (as regular orders), which already include the deliveries aim to bring the stock to within the acceptable limit.

Pseudo PID (see Test FM-1d) is shown to reduce the average variation in order quantity set to printer. Although the time to return to steady state is relatively large (slow response), this may not be a disturbing factor considering that the average stock level at packer/filler is relatively low compared to the case with the (*s,S*) policy or the smooth average policy.

VMI is shown to keep the average stock level low, but the average variation in order quantity set to printer is considerably high. The reason for the large variations is due to the number of orders issued being approximately double compared to other policies, and the quantity being ordered between one order and the next are not the same.

#### 6.6.3.2 Type III-Faulty material: Part 2- Random simulation

Further tests were performed assuming that the amount of faulty material is random. To test the effectiveness of the (*s,S*) policy, the pseudo PID policy, the smooth average policy and VMI policy, five sets of simulation runs (replications) were conducted. Different streams of random numbers were used for each of the five simulation runs to model a stochastic/random disturbance on each delivery. The tests were subjected to the following: a maximum of 5% faulty material, with a mean of approximately 3%, and the simulation time was 200 days. In each run, the average stock level at packer/filler were tabulated.

The average stock level in packer/filler were as follows:

**Table 6-5b** Samples of average inventory level at packer/filler for different random input demand pattern from retailer

| Policy | Replication 1 | Replication 2 | Replication 3 | Replication 4 | Replication 5 |
|---|---|---|---|---|---|
| (s,S) | 585 | 580 | 583 | 582 | 580 |
| Smooth average | 590 | 622 | 621 | 561 | 565 |
| Pseudo PID | 558 | 548 | 553 | 554 | 545 |
| VMI | 321 | 318 | 316 | 323 | 323 |

The figures in Table 6-5b suggests that VMI is the most effective in keeping low stock levels at the packer/filler. A decision-maker would want to know which of the other three policies, (excluding the VMI) is performing better. Do these figures demonstrate a significant difference between (*s,S*) policy, the smooth average policy, and the pseudo PID policy?

Such an analysis is performed using 'hypothesis testing'. Hypothesis testing is a way of asserting that a particular value, a mean for a sample of data for example, is equal to a proposed value, for example 0 (named as the null hypothesis $H_0$), or alternatively asserts that the mean does not take this value (named as the alternative hypothesis $H_1$). More detailed discussions on the construction of hypothesis testing for simulation

model results can be found in, for example Robinson [Robinson 94], Banks *et. al.* [BanksCN 96] and Law and Kelton [LawK 00]. The test used in this analysis is known as the 'paired sample *t* test'. The theory behind this hypothesis testing can be found in, for example [Rees 01].

With *d* being difference in the inventory levels achieved between two policies being compared, the hypothesis can be stated as:

$$H_0 : d = 0$$
$$H_1 : d \neq 0$$

The confidence interval for the mean of a population of differences for paired samples data is given as:

$$\bar{d} \pm \frac{ts_d}{\sqrt{n}} \qquad (6.1)$$

where the mean $\bar{d}$ and standard deviation $s_d$ of the differences are given by:

$$\bar{d} = \frac{\sum d}{n} \quad \text{and} \quad s_d = \sqrt{\frac{\sum d^2 - \frac{(\sum d)^2}{n}}{n-1}} \qquad (6.2)$$

*t* is a threshold based on required level of confidence,
*n* stands for the number of differences (= number of pairs).

Test statistic *T* for testing a population of differences, is given by

$$T = \frac{\bar{d}}{\frac{s_d}{\sqrt{n-1}}} \qquad (6.3)$$

$-t_{95} < T < +t_{95}$ accept $H_0$

otherwise accept $H_1$.

where $t_{95}$ is the threshold of 95% level of confidence for *t*-distributed variables.

The value of *T* is obtained from the Percentage points of the *t* distribution given in Appendix I.

(a) Do these results provide any evidence to say that the smooth average policy performs better than the (*s,S*) policy in reducing the inventory level?

For the difference of average inventory level (implementing (*s,S*) policy – average inventory level (implementing smooth average policy), based on the five replications, the differences have mean, $\overline{d} = 9.8$, and standard deviation, $s_d = 29.24$ .

We test $H_0$ against $H_1$.

If $H_0$ is true, then $T \sim t_{n-1}$

The test state in this case is then $T$=0.6703, see Figure 6-8.

For $T \sim t_4$, the 5% rejection region is for $t_{95} = 2.132$ , and since $|T| < t_{95}$, we accept $H_0$ . Hence, there is no evidence that the *smooth average policy* performs better in reducing the inventory level, compared to the *(s,S) policy.*

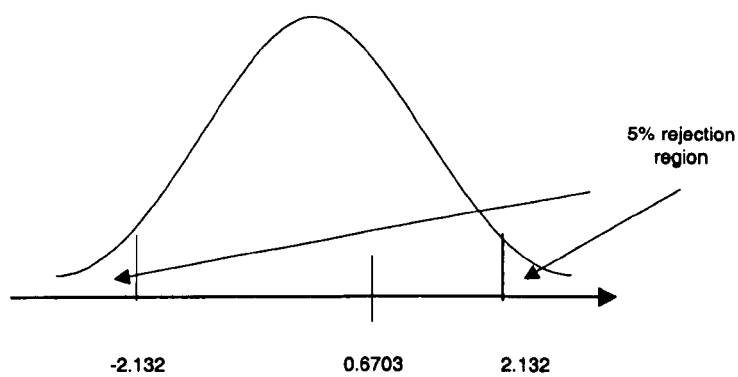



**Figure 6-8.** ***t*** Distribution for $n$=4 Degrees of Freedom and the location of $T$=0.6703.

Accordingly, a similar test were performed to answer the following question:

(b) Do these results provide any evidence to say that the smooth average policy performs better than the pseudo PID policy in reducing the inventory level?

These five differences have mean, $\bar{d} = 40.2$, and standard deviation, $s_d = 29.55$.

The test state in this case is then $T$=2.721

For $T \sim t_4$, the 5% rejection region is for $t_{95} = 2.132$ , and since $|T| > t_{95}$, we accept $H_1$.

The test gives an evidence that the smooth average policy may cause the packer/filler company to carry larger inventory.

Hence, the two tests give evidence that the *pseudo PID* policy performs better in reducing the inventory level, compared with the *smooth average* policy and the (*s,S*) policy.

#### 6.6.3.3 Type III-Late delivery

Two tests were performed. First test is a comparison on the effectiveness of each scheme (inventory policies) to the occurrence of late deliveries. The second is an analysis on the effect of the late deliveries that last for a certain duration of days, on the risk of stock-outs and to the number of undelivered items (batch ordered).

**The first set of tests:**

A comparison on the effectiveness of each scheme (inventory policies) due to late deliveries is investigated here.

**Table 6-6.** Comparison on the effectiveness of the decision (policy) in the presence of disturbance (late deliveries, duration of 4 days), based on the performance metrics.

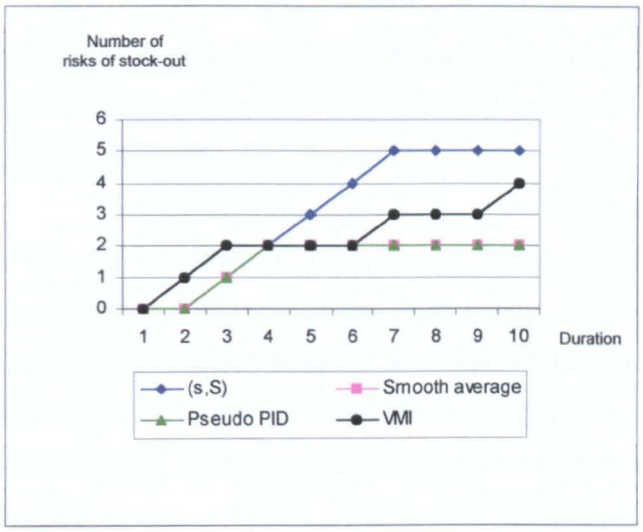
| Performance metrics | Order decision at packer/filler, $u_D$ | | | | |
|---|---|---|---|---|---|
| | **Test LD-a** *Generic* | **Test LD-b** *(s,S)* | **Test LD-c** *Smooth averaged* | **Test LD-d** *Pseudo PID* | **Test LD-e** *VMI* |
| Time to return to steady state (in days) | 14 | 28 | 14 | 63 | 24 |
| Average stock levels at D $I_{Dav}$ ,and | 770 | 655 | 770 | 690 | 390 |
| at C $I_{Cav}$ | 2759 | 2632 | 2759 | 2585 | 2971 |
| Maximum order quantity to printer, $u_{Dmax}$. | 700 | 1400 | 700 | 810 | 700 |
| Average variation in order quantity set to printer | 100 | 160 | 100 | 147 | 180 |
| Number of emergency orders, *E* at day *d* | 1 | 0 | 1 | 1 | *NR* |
| Risk of stock out. | 2 | 2 | 2 | 2 | 3 |
| Number of order batch undelivered | 1 | 1 | 1 | 1 | 2 |

*Note:*
*NR- not relevant since no emergency orders were generated. For* VMI, the printer is sending goods (printed labels) twice a week (as regular orders), which already include the deliveries aim to bring the stock to within the acceptable limit.

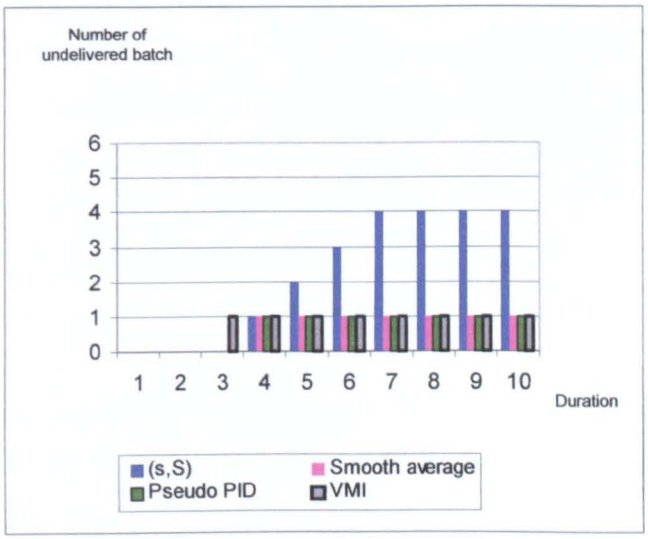
Table 6-6 compares the effectiveness of the different control scheme (inventory policies) to late deliveries, lasting 4 days. The summary of the findings is as follows: Tests LD-1a, and LD-1c indicate that the generic policy and the smooth average policy have the same effectiveness in regulating the inventory at the packer/filler. The (*s,S*) policy (Test LD-1b) can keep the average inventory level low, but the order issued to printer company is larger than the other policies. The Pseudo PID is slow to reach steady state, but performs well in other aspects of performance. The VMI (Test LD-1e) is the most effective in keeping the stock level low, but the average order variations made to the printer is relatively high. Another observation is that the risks of stock-out and the number of batch undelivered is large for VMI, compared to the other policies. This implies the limitation of VMI in handling the risk of stock out in the event of late deliveries.

**The second set of tests**:

The analysis is on the effect of the late deliveries lasting a certain duration of days, on the risk of stock-outs and to the number of undelivered items.




**Graph a**. Risk of stock-outs versus duration of late deliveries.




**Graph b**. Number of undelivered items (batch ordered) versus duration of late deliveries.

**Figure 6-9**. Risk of stock-outs and the number of undelivered batch for a specified duration of late deliveries.

Graph a of Figure 6-9, shows that for (*s,S*) policy, the risks of stock-out increases almost linearly from one (duration of 3 days of late delivery) to five (duration of 7 days of late delivery), and then settles to five (duration of 8 days onwards of late deliveries).

For the smooth average and the pseudo PID policies, at first the risks emerges with just one (from duration of 3 days of late delivery) and then settles to two from duration of 4 days onwards of late deliveries.

Graph b indicates that the number of undelivered items (ordered batch) were maintained with 1 for all policies, except for the (*s,S*) policy. For the (*s,S*) policy the number of undelivered batch increases linearly and then stabilises to 4 occurrences from duration equals 7. In the case of VMI, although the risks may be greater compared to smooth average and pseudo PID policies, the actual number of undelivered batch was the same.

The results indicate that the smooth average, and pseudo PID policies perform well in keeping the number of stock-outs low.

## 6.7 Overall summary of results

A number of conclusions can be drawn from these examples. The (*s,S*) policy is shown to be robust in keeping the risk of stock-out low in the case for Test PD-1a. On the contrary, the tests on late deliveries show that its performance deteriorates when the risks of stock-outs and the number of undelivered batches ordered for a given duration of late in days were compared. The VMI policy dominates in its ability to reduce the average stock level at the packer/filler. However, it is very sensitive to disturbances, where the risks of stock-outs are the highest (see Tests PD-1d, MB-1e, MB-2e, FM-1e, LD-1e), compared to other policies.

Both the smooth average and the pseudo PID policies, in all tests, exhibit similar performance in keeping the risks of stock-outs low. Both policies are also shown to be robust to the risks of stock-outs and the number of undelivered batches ordered for a given duration of late delivery in days. The pseudo PID policy, however, is shown to be better than the smooth average policy when comparing the effectiveness in keeping the stock level at the packer/filler lower (see results in section 6.6.3.2).

The simulation tests presented here (as well as in Chapter 5) show that many aspects of a supply chain can be modelled, simulated, analysed and understood effectively with the aid of a DSS, in this case a DES simulation model of a FMCG supply chain. However, it is important to note that a DSS does not make a decision, instead assists, supports and recommends the human decision-maker in the decision making process.

A decision-maker will need other information such as ordering costs, transportation costs, holding costs, etc., to decide on an effective policy. The information in these tests would assist a decision-maker to propose a policy that achieve some combination of low cost and high customer service.

## 6.7 Summary

This chapter illustrates with several examples the use of a simulation model to study the effectiveness of a decision policy (inventory policy) to counter the disturbances that are due to fluctuations in the retailer orders, the occurrences of machine breakdowns, faulty materials, and late deliveries.

Results revealed the robustness of the various decision policies to the different types of disturbances. In particular, it was seen that pseudo PID, a policy derived from the control system view point, exhibited much more robustness than other policies, whereas VMI fared rather poorly.

The results that have been presented from the analysis are useful for a decision-maker at the packer/filler to anticipate what the consequences would be of a particular type of policy if certain events such as changes in demand patterns, manufacturing disturbances, and inventory disturbances took place.

The model developed in this work was limited to the analysis of situations that have been discussed in this thesis. However, the modelling and simulation for other disturbances for example, the decision making at another company, for instance the printer company, would be similar and straightforward to what that has been presented.

# Chapter 7

# Conclusions and Future Work

## 7.1 Conclusions

The aim of this thesis has been to develop a decision-support system (DSS) of a fast moving consumer goods (FMCG) supply chain with a DES tool. The DSS can be utilised for the investigation of the effectiveness of several inventory policies towards effective coordination and control of a production-inventory system, and their effectiveness in the presence of disturbances.

This thesis discusses fundamental issues in the development of a simulation model for a supply chain using discrete-event simulation (DES) tool, ARENA, and has covered two main issues: development of the model and the experimental design. In particular it has been organised to answer questions such as what modelling approach is needed to produce a simulation model of a supply chain system; how to implement the approach and build a simulation model; how to verify and validate the simulation model (in this case when real data are not available); how to specify problems and scenarios to be analysed (experimental design); how to extract useful information for comparisons, for example the effects of inventory policies; and how to devise and evaluate some performance measures in the presence of disturbances in the manufacturing and market conditions.

The use of simulation to offer insights into a supply chain when balancing the customer service level requirements with profits cannot be ignored. Chapter 3 describes a modelling approach undertaken to produce a computer simulation model of a supply chain system using a discrete-event simulation (DES) language. This includes an explanation on the design of a conceptual model of the supply chain system, and the design and development of an implementation model based on the conceptual model associated with the ARENA simulation language.

Chapter 4 takes another step in the modelling procedure and discusses the verification and the validation processes that have been adopted. This is to illustrate that the simulation model performs as expected and intended and thus establishes that the model behaviour validly represents that of the system being simulated.

A DES simulation model forces the understanding in a systematic way, of how a system operates and thus defines the system clearly and minimises multiple interpretations as to the complexity and variability of the processes involved. Some examples to illustrate the application of the simulation model in evaluating the effectiveness of several supply chain policies were given in Chapter 5. Several tests were formulated and conducted based on observation of some real-life processes, where the performances of each case (inventory policy) were compared and analysed. The particular work conducted in this chapter is the identification and understanding of the complex relationships that occurs in a supply chain system, for example, in the occurrences of uncertainties, or disturbances. The primary emphasis of the experimental work is placed on evaluating the supply chain performance focusing on the 'flexibility' aspects, where different ordering policies have been compared and analysed. Meaningful analysis must consider the ability of the system to respond to accommodate demand variations. Several tests with different input pattern (demand variation's from retailer) have been studied.

Chapter 6 extended the model that has been developed in the previous three chapters (Chapters 3 ~ 5) where some additional design requirements were introduced. Meaningful analysis for revealing the complex behaviour of the supply chain system must consider ways of modelling the system and the relations to its contextual components, that is, how the supply chain system would react to its environment. The *contextual load* modelling is conducted in this work with the realisation that meaningful investigation of a particular system, in this case the supply chain system, indeed can be achieved by explicitly accounting for its environment. The task of developing the *contextual load* model requires the identification of the possible sources of disturbances that might exist in the system, the modelling of these disturbances and the particular parameter(s) in the model that are to be changed to simulate such disturbances. The purpose is to address several issues particularly on whether decision policies would provide stability in the presence of disturbances, as

well as evaluating the effect of disturbances on the process (the supply chain system). Several tests have been devised, and some performance metrics that measure the 'adaptability' of the system to disturbances have been considered.

The DSS developed in this work could be used by a decision-maker to augment his operational decision-making capabilities. If the decision-maker can understand the supply chain dynamics and variability behaviour, and make changes to the supply chain based on this understanding, better performance from the supply chain can be expected, for example a chain with lower inventories and better customer service.

The main contributions of this work are:

- As existing tools are not adapted to modelling the decision process, this work demonstrates the steps taken in developing a simulation model for a supply chain, incorporating and co-ordinating the interrelations of the companies in one model, by utilising applicable concepts that exist in DES, in particular the ARENA simulation tool.

- As a DSS, the simulation model represents important characteristics of a FMCG supply chain and incorporate the complex interactions that may exist between the various components in the system. Importantly, the model was designed with easily adaptable structure where rules (inventory policies) and model variables can be modified. By devising appropriate experimental design, several tests can be performed to imitate some realistic situations (the presence of disturbances). The results can then be analysed to provide information to a decision-maker from which solutions can be inferred.

- The detailed comparisons of five inventory policies (the generic, the $(s,S)$, the smooth averaged, the pseudo PID and the vendor-managed inventory (VMI)) for a production-inventory control under dynamic and stochastic conditions were given. The pseudo PID policy, which has not been reported elsewhere, has been shown to have several advantages as an inventory control policy. Qualitative behaviour of supply chain to different policies were confirmed through detailed quantitative analysis.

- By adopting the control system viewpoint, a pseudo PID inventory control policy has been proposed. This paves way for ideas from control system theory to be utilised in deriving new policies.

## 7.2 Directions for future Work

The development of a simulation model of a supply chain using DES tool is a relatively new approach, considering its application for an operations research (OR) problem. The modelling, simulation, and analysis of a supply chain discussed in this thesis are a preliminary attempt to establish a methodology for modelling, simulation and analysis of a supply chain using a DES. There are further problems to be considered both in the development of the model and the experimental design.

Future work should include:

- Development of a decision-support system for supply chain.
  Developing a decision-support system (DSS) software on the basis of the proposed approach with the consideration of more general and easy building blocks, and taking practical situation into account, would be beneficial. The particular emphasis should be given on development for a larger and demanding systems, such as multiple suppliers, and multiple customers (retailers).

- Verification and validation of the modelling approach.
  Applying the modelling approach to a different type of supply chain topology, in order to verify and validate the technique under different classes of systems will demonstrate the generality of the approach. The issue of verification and validation when real data are available has not been done here. If such data were available, integrating the method advocates in this thesis with that based on real data would be an interesting paradigm in verification and validation.

- Multiple supply chain performance analysis.
  The analysis that includes a combination of several performance measures, for example costs, customer responsiveness, as well as flexibility measures as outlined in Chapter 5 for the evaluation of a supply chain system's performances, would be very useful.

- Modelling multiple disturbances.
  Although the *contextual load model* presented in Chapter 6 can simulate the complex behaviour of the supply chain from various scenarios, it is still not sufficient for most applications because the outcome of the analysis are based on the assumption that each disturbance occurs independently. The extension on the *contextual load* modelling, to understand how each controller (inventory policy) reacts to a combination of several disturbances (multiple disturbances), would still be required.

- Evaluation of inventory control policies.
  The evaluation of other inventory policies that already exist, and the modelling and evaluation of newly proposed inventory policies, for example new control theory motivated policies such as gain scheduling incorporated into the pseudo PID inventory control model, to provide insights and better understanding of each of the inventory control policy, would need to be explored.

The work presented in this thesis has contributed to an improved understanding of the procedure for modelling, simulation and analysis of a supply chain system with a discrete-event simulation tool. Even though the approach presented here offers some promising tools, much work remains to be done to produce a systematic methodology for building a model of high complexity in nature, like the supply chain.

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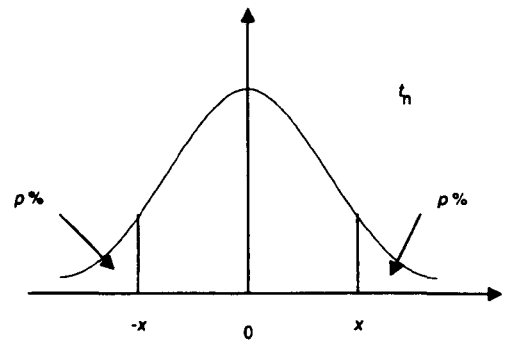
## Appendix I : Percentage points of the *t* distribution




| *p* % | | 0.05 | 0.025 | 0.01 | 0.005 |
|---|---|---|---|---|---|
| *n* = | 1 | 6.314 | 12.71 | 31.82 | 63.66 |
| | 2 | 2.920 | 4.303 | 6.965 | 9.925 |
| | 3 | 2.353 | 3.182 | 4.541 | 5.841 |
| | 4 | 2.132 | 2.776 | 3.747 | 4.604 |
| | 5 | 2.015 | 2.571 | 3.365 | 4.032 |
| | 6 | 1.943 | 2.447 | 3.143 | 3.707 |
| | 7 | 1.895 | 2.365 | 2.998 | 3.499 |
| | 8 | 1.860 | 2.306 | 2.896 | 3.355 |
| | 9 | 1.833 | 2.262 | 2.821 | 3.250 |
| | 10 | 1.812 | 2.228 | 2.764 | 3.169 |
| | 11 | 1.796 | 2.201 | 2.718 | 3.106 |
| | 12 | 1.782 | 2.179 | 2.681 | 3.055 |
| | 13 | 1.771 | 2.160 | 2.650 | 3.012 |
| | 14 | 1.761 | 2.145 | 2.624 | 2.977 |
| | 15 | 1.753 | 2.131 | 2.602 | 2.947 |
| | 20 | 1.725 | 2.086 | 2.528 | 2.845 |
| | 30 | 1.697 | 2.042 | 2.457 | 2.750 |
| | 50 | 1.676 | 2.009 | 2.403 | 2.678 |
| | 100 | 1.660 | 1.984 | 2.364 | 2.626 |
| | ∞ | 1.645 | 1.960 | 2.326 | 2.576 |

*n* is the degrees of freedom.

Source: From Table C.5 Percentage Points of the *t* distribution, by D.G. Rees Essential Statistics, Fourth Edition, Chapman & Hall/CRC, 2001.