SYSTEM DYNAMICS MODELLING OF CLOSED LOOP SUPPLY CHAIN SYSTEMS FOR EVALUATING SYSTEM IMPROVEMENT STRATEGIES

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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July 2010

CANDIDATE'S CERTIFICATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of the work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Signed: ____________________________________

Name: Roberto Poles

Date: ____________________________________

ACKNOWLEDGEMENTS

The PhD thesis is a lonely and hard journey. Several people and institutions have helped me along the way in different ways. I take this opportunity to thank them and acknowledge their contributions. First and foremost, I am very grateful to my senior supervisor, Dr France Cheong, for his tireless and continuous feedback, advice, editing and support during these years of the journey. I would also like to thank my second supervisor, Professor Brian Corbitt, for his friendship and moral support during the critical stages of the journey.

I am grateful to RMIT University, especially to Professor Brian Corbitt and Ms Prue Lamont, for the financial support provided through the Australian Postgraduate Award, RMIT Business Portfolio Postgraduate Research scholarship, and funding for attending conferences and publishing papers. The scholarship and the funding were a fundamental support to carry out this research.

I would also like to thank my wife, Alexandra Poles, and my parents, Eduardo and Raffaella Poles, for supporting my educational goals and for their continuous encouragement, unconditional love and belief in me.

I would like to acknowledge the professors and staff members from the School of Business Information Technology and Logistics for providing a very good working environment. I also need to acknowledge Professor Kosmas Smyrnios, Dr David Wilson and Mr Peter Dapiran from the School of Management for their useful support and advice. David, thanks for being a friendly person, sorting out whatever problems I had.

I take this opportunity to express gratitude to all the participants from the industry world with who I had the pleasure of working in this research project. A special thank-you goes to Dr Dan Godamunne and Mr Veera Chippada from Fuji Xerox Australia and Mr Alex Oldfield from CEVA Logistics for having given me the opportunity to visit several times their companies and collect data and information very useful and fruitful for this research.

I am also grateful to my research colleagues, Warren Staples, Anuja Cabraal, John Leavesley, Suryadeo Vinay Kissoon, Patricia Eisele and Sully Taulealea for all the support, encouragement and friendship during these years. I will never forget our private study room on level 7.

I must not forget my editor, Julia Farrell, and all the anonymous reviewers of the various papers for their comments very useful to improve the quality of this thesis. Last, but not least I owe profound gratitude to God, who makes all this possible.

DEDICATION

I dedicate this thesis to my child who will be born in August 2010 and to my wife, Alexandra. Her love, efforts, understanding and support made this study possible.

CREDITS

The following book chapter and papers were written as part of the research of this thesis:

1. Poles, R. (2010) ‘Modeling Closed Loop Supply Chain Systems’, In *Advanced Analytics for Green and Sustainable Economic Development: Supply Chain Models*, IGI Global Publisher (book chapter accepted).

2. Poles, R. & Cheong, F. (2010), ‘An Investigation on Capacity Planning and Lead Times for Remanufacturing Systems Using System Dynamics’, *HICSS-44*, paper under review.

3. Poles, R. & Cheong, F. (2010), ‘A system dynamics model for inventory control in Closed Loop Supply Chain’, *International Journal of Logistics Research and Application*, paper under review.

4. Poles, R. & Cheong, F. (2009), ‘Inventory Control in Closed Loop Supply Chain using System Dynamics’, *The 27th International System Dynamics Conference 2009*, 27-31 July 2009 Albuquerque, New Mexico, USA.

5. Poles, R. & Cheong, F. (2009), ‘A System Dynamics model for reducing uncertainty in remanufacturing systems’, *Pacific Asia Conference on Information Systems (PACIS) 2009*, 10-12 July 2009 Hyderabad (India).

6. Poles, R. & Cheong, F. (2008), ‘Modeling remanufacturing systems with uncertainty of returns using System Dynamics’, *Australian and New Zealand Academy of Management (ANZAM) 2008*, 2-5 December 2008 Auckland (New Zealand).

7. Poles, R., Dapiran, G.P., Wilson, D. & Rahman, S. (2007), ‘Closed Loop Supply Chain modeling’, *The 5th International Conference on Supply Chain Management and Information Systems*, 9-12 December 2007 Melbourne (Australia).

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ABSTRACT

In the past, many companies were concerned primarily with managing activities along the traditional supply chain in order to optimise operational processes and thereby economic benefits, without considering new economic and environmental opportunities in relation to the reverse supply chain and the use of used or reclaimed products. In contrast, there is now increasing interest among companies in reverse logistics and closed loop supply chain (CLSC) and their economic benefits and environmental impacts. In particular, the concept of CLSC views the reverse flow (i.e. the reverse supply chain) of reclaimed goods as integral to the forward flow (i.e. the traditional supply chain) to the consumer. At the end of the useful life of products, a reverse supply process is activated in which unwanted materials and products are recovered from end users to recapture some of their value. Therefore, planning for the forward flow of goods must take into account the recovered products. Three main processes that need to be considered are: (1) collection and distribution planning; (2) inventory control; and (3) production planning.

In this thesis, our focus is the study of remanufacturing activity, which is one of the main recovery methods applied to closed loop supply chains. Specifically, we investigate and evaluate strategies for effective management concerning inventory control and production planning of a remanufacturing system. In order to pursue such a research objective, we model a production and inventory system for remanufacturing using the System Dynamics (SD) simulation modelling approach. Our primary interest is in the remanufacturing and returns processes of such a system.

As part of the development of the SD models, we identify the main factors, their influence relationships and the business/operational policies that affect the dynamic behaviour of the system. The returns process is modelled using significant factors which define: (1) the average period of time for which a product stays with its customer before it is returned (*residence time*); (2) the incentives offered by companies for the recovery of the used products (*service agreement with customer*); and (3) the behaviour of customers in returning used products (*customer behaviour*). Interestingly, combining these factors in a process model addresses the issue regarding the uncertainty in quantity and timing of returns in the reverse supply chain. To our knowledge, a returns process modelled with such factors and their influence relationships is not readily available in the literature. For the same system, the remanufacturing process is modelled using such key factors as: (1) integrated remanufacturing/production capacity, (2) lead times, (3) backorder and (4) inventory coverage. Several policies that affect the dynamic behaviour of the system are defined in the modelling process using such factors. These modelled policies are included in order to improve the efficiency of managing production/remanufacturing and inventory activities in the process.

This thesis also contributes to the field through the analysis of several scenarios combining the aforementioned factors and utilising simulation in order to evaluate strategies aimed at the optimum performance of the system. The evaluation results reveal that efficiency in managing inventory can be improved by increasing the returns rate (quantity of returns), which in turn can be achieved by reducing the residence time and increasing company incentives for the recovery of used products. At the same time, the uncertainty around the returns rate is significantly diminished by increasing those incentives that encourage customers to return used products. Other findings indicate improved efficiency in the remanufacturing process with higher remanufacturing capacity if the quantity of remanufacturable returns and the remanufacturing lead time are increased and decreased, respectively. Moreover, increasing the production lead time affects system performance more than does an equivalent increase in the remanufacturing lead time.

Case studies are used in this thesis in order to support some of the research findings and to further validate the developed models of the production and inventory system for remanufacturing. The selection of companies employed as case studies was based on their engagement in remanufacturing and returns processes, which made them useful for our research. Specifically, data and information were collected through interviews with company management representatives of the Australian Mobile Telecommunications Association, Fuji Xerox Australia and CEVA Logistics. These three companies are significantly involved in operational and management activities linked to reverse logistics and remanufacturing processes. The knowledge gained about these companies' activities, coupled with the data collected from the 'real world', were useful for the development of the models of returns and remanufacturing processes as well as for the assessment of the research findings.

Chapter 1

INTRODUCTION

The research undertaken in this thesis investigates business and operations management strategies to improve the performance of remanufacturing systems within the context of closed loop supply chains. This chapter introduces the exploration of the concepts of reverse logistics and closed loop supply chain (CLSC) and their economic and environmental impacts on business. It presents the aim and justification for this research. It also provides a brief discussion of the methodology utilised and the research contributions offered by this thesis. Finally, an outline of the thesis is provided.

1.1 Background

The ever-increasing number of manufactured products requires ever more natural resources, as trillions of tonnes of different forms of natural resources (e.g. raw materials, energy and water) are needed for the manufacturing process (Gungor & Grupta 1999). However, society and industry have both come to recognise the limited availability of natural resources and are moving towards the manufacture of more environmentally friendly products and the recovery of resources. For this reason, the modern trend, particularly for developed countries, is to use fewer environmental resources such as energy, water, air and raw materials to manufacture products. Moreover, interest in strategic sustainability is growing among multinational companies, and they are developing sustainability reports to demonstrate both their concern for the environment and their responsibilities toward socio-ecological activities when conducting business. In addition, sustainability can be used as a competitive strategy to create company branding, comply with government regulations regarding the environment and optimise the cost of operational processes.

This burgeoning economic and environmental consciousness within business has increased the focus on reverse logistics activity (company processes that recapture value from product returns) over the last decade (Blumberg 2005). Indeed, this reverse logistics activity, particularly remanufacturing (the process of reusing returned products in production), can play an important role in sustainability as well as in competitive strategies aimed at reducing the use of natural resources and recovering value from used products. However, several factors make the development of reverse logistics processes difficult. In particular, the complex integration between the forward (from the producer to the consumer) and the reverse (from the consumer to the producer) supply chains can negatively affect operations and logistics management activities such as production planning, inventory control and distribution planning.

In this thesis, our primary interest is the remanufacturing and returns processes in the context of closed loop supply chains which, through integration between the forward and the reverse supply chain, represents a new concept within reverse logistics systems. Our study focuses on production and inventory management which is one of the main domains of research within this field (Kleber 2006).

The concepts of reverse logistics and closed loop supply chain are introduced and explained in detail in the following sections.

1.1.1 Reverse Logistics

According to the Reverse Logistics Executive Council, reverse logistics is the process of moving goods from the point of consumption to the point of origin for the purpose of either recapturing value or proper disposal. Stock (2001) has defined reverse logistics as:

> *the term most often used to refer to the role of logistics in product returns, source reduction, recycling, material substitution, reuse of material, waste disposal, and refurbishing, repair and remanufacturing.*

Several methods of recapturing value from returns can be pursued and several types of recovery methods can be carried out by companies (Kulwiec 2006). Products can be reused directly after cleaning or reconstruction. This is a common practice for items such as used pallets, bottles/glass or containers. For example, a case study was undertaken in Denmark in which 65,000 tonnes per year of glass was collected, inspected, washed and later reused (Jonishi 2006). However, products whose parts or materials may be repaired or replaced can be reused after repair as rebuilt or used products.

Another method of recovery is remanufacturing, a process in which parts and materials from returned products are reused for production. Remanufacturing requires more extensive work, since the returned product must be completely disassembled, its parts and modules examined and either repaired or replaced, and then reassembled into a new product. Remanufacturing is practised in many industries, including for photocopiers, computers, telecommunications equipment, automotive parts, office furniture and tyres. This method entails annual sales of remanufactured products in excess of US$53 billion each year and more than 73,000 firms are engaged in remanufacturing in the US (Mitra 2007).

A final recovery option is recycling. In this case, some or all of the parts and materials from returned products can be processed to make different products (Kulwiec 2006).

Recycling occurs in the paper, plastics and metals industries. For example, in the US, 20% of glass, 30% of paper products and 61% of aluminium cans are recycled. Moreover, 95% of the 10 million retired cars and trucks each year go to the recycler and 75% by weight of these are recovered for reuse (Gungor & Grupta 1999).

To clarify the reverse logistics concept, Figure 1.1 depicts a typical reverse logistics process for used products in a supply chain.

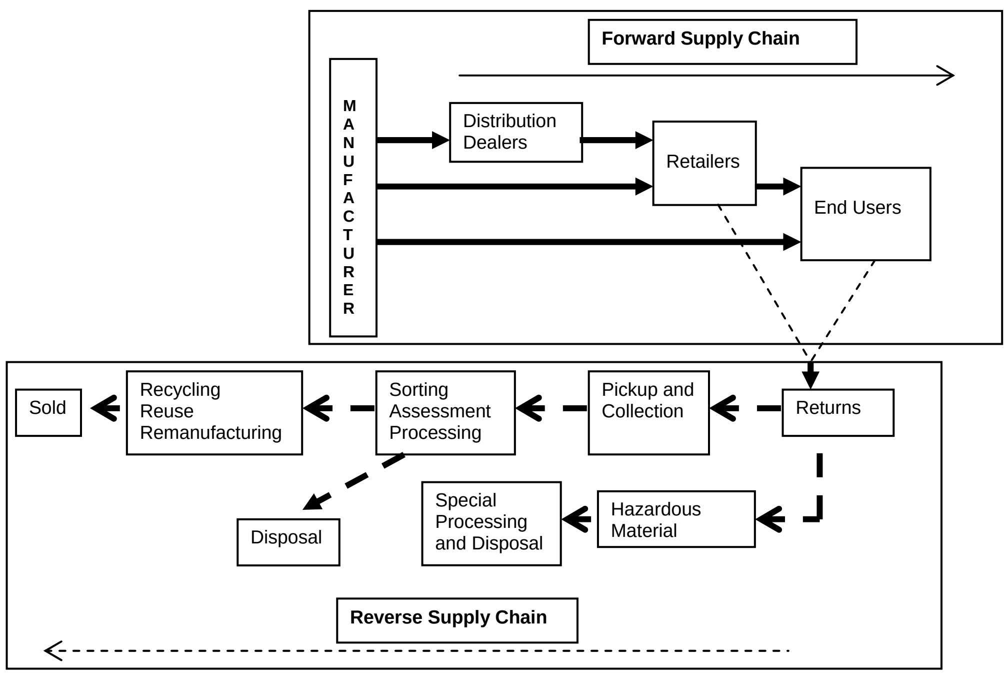


Figure 1.1: Reverse logistics process (adapted from Blumberg (2005))

In the forward flow, the product moves from the manufacturer to the consumer or end user typically through distributors and retailers. In the reverse flow, returned unwanted materials and products from end users and retailers reach their final destination by passing through several reverse logistics activities. These are pickup/collection of returns; sorting; assessment and processing to assess reusability and identify materials; recycling;

reuse; and remanufacturing. Hazardous materials need to be processed separately for specialised handling and disposal.

1.1.2 Closed Loop Supply Chain

The concept of reverse logistics has changed in recent years (Dekker et al. 2004). More specifically, the concept of a closed loop supply chain (CLSC) has been developed to refer to the complete loop from the customer, back to the plant, through a reprocessing operation, and then back to the customer (French & LaForge 2006). Closed loops consist of two integrated supply chains—a forward and a reverse chain—through which a recovered product re-enters the original forward chain (Wells & Seitz 2005).

Figure 1.2 represents the more comprehensive nature of a CLSC, including the various ways by which value can be captured: reuse for remanufacturing, returns for redistribution, and repair/refurbishment for other distribution channels or secondary markets. This reverse logistics component is sometimes treated as an extension of the traditional concept of supply chain management. In this case, reverse logistics is not managed independently of forward logistics, but rather both processes form part of a complete supply chain process whereby products start with the manufacturer to reach the customer, then come back to the plant and back again to the customer. This process has been defined as a new concept, referred to as the 'closed-loop supply chain' (Eoksu et al. 2004). Figure 1.2 depicts this closed loop between manufacturer and customer or retailer. In this scenario, the final stages of the reverse supply process to recapture value from returns include reuse for remanufacturing, returns for redistribution and repair/refurbishment for other distribution channels or secondary markets. The qualification stage, involving selection on the basis of the quality of returns, is a more involved activity of sorting to reuse components and sub-assemblies or to dispose of non-reparable whole units.

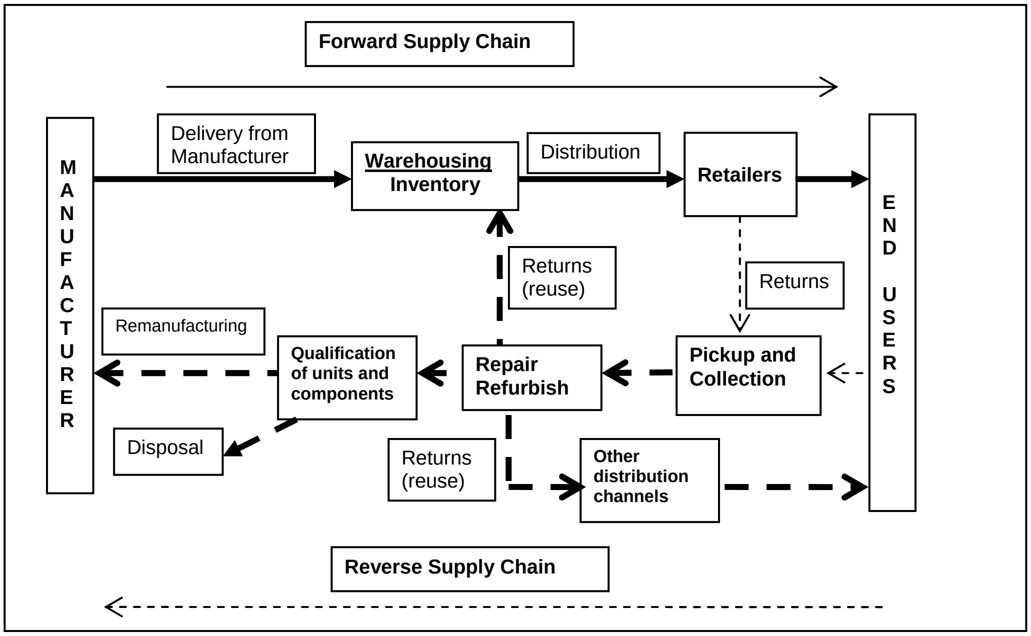


Figure 1.2: Closed Loop Supply Chain (adapted from Blumberg (2005))

In the past, companies focused their competitive efforts between single activities or actors within the supply chain, but have more recently realised that competition takes place between entire supply chains (Lourenço & Soto 2002). This has opened new opportunities of research in this field to improve company performance. Closed loop supply chains require more attention on larger strategic issues rather than on operational aspects, including traditional forward supply chain activities and the additional activities of the reverse supply chain (Guide, Harrison & Wassenhove 2003).

1.2 Aim and Scope of Thesis

The integration of reverse logistics activities within the structure of the original production and distribution systems leads to additional complexity in the closed loop supply chain system. This complexity, which can hinder the integration process, comes from the significant differences between the forward and the reverse supply chains. The latter are characterised by operational and business factors which disrupt the traditional approach to dealing with supply chain management. Examples include: (1) reverse distribution from many points (customers or retailers) to one point (manufacturer); (2) the complexity of forecasting returns; (3) a lack of uniformity in returns quality; (4) reverse logistics costs being less directly visible; and (5) production and inventory management being affected by the flow of returns. These are all factors which lead to the necessity to rethink and replan the original supply chain. In particular, in the context of the remanufacturing process, production and inventory management entail the added complexity of coordination between the remanufacturing and production activity in terms of size of orders and lead times. Moreover, such coordination must account for the new kind of inventory generated by the additional flow of collected returns to be integrated into the remanufacturing process. However, this additional flow is not directly available to the manufacturer because of the unpredictability of the quantity, timing and quality of the products returned by customers.

The uncertainty around the quantity and timing of returns is one of the main factors that make the implementation of closed loop supply chain processes difficult, particularly for integration between the forward and reverse supply chains. For example, the difficulty of determining the quantity of used products to be returned by customers negatively affects remanufacturing and traditional production planning. Moreover, the lack of tools and guidelines on planning, controlling and managing remanufacturing operations has limited the growth of the remanufacturing sector (Guide 2000). If not well designed, closed loop supply chain activities such as remanufacturing and disposal can increase company costs (Inderfurth 2005). For this reason, a company objective is to integrate the reverse and forward supply chains so as to minimise the total cost and consequently obtain economic benefits.

Mindful that these problems add complexity to this field of research, in this thesis we aim primarily to model the factors affecting a production and inventory system that combines returns and remanufacturing, and to evaluate effective control strategies that address dynamic production and inventory management issues in order to improve the performance of the system. For this purpose, models of a production and inventory system for remanufacturing within the context of closed loop supply chains are used in order to understand the complex and dynamic interaction of factors that affect the behaviour of the system. Moreover, these models are used to evaluate strategies for effective management of the remanufacturing and returns processes.

1.3 Justification for the Research

In the United States, the precise extent of reverse logistics activities is difficult to determine because most companies have not quantified them (Reverse Logistics Executive Council 2007b). However, reverse logistics activities account for a significant portion of logistics costs in the US. These are estimated to account for approximately 10.7% of the US economy and approximately 4% of the total logistics costs (Reverse Logistics Executive Council 2007b). Reverse logistics costs are estimated at approximately to 0.5% of total US gross domestic product (GDP), which equated to approximately US$58.34 billion in 2004. In 1999 the total value of returned merchandise in the US, with an estimated handling cost of $40 billion, was $62 billion (ReturnBuy 2000). The US is not the only country where reverse logistics activities are increasing. In Europe, the annual production of remanufactured automotive parts was approximately 20,000,000 units in 2005, with an expected increase to 30,000,000 units in 2015 (Automotive Parts Rebuilders Association 2007). In Australia, the Eco Manufacturing Centre of Fuji Xerox, a company that continually adopts new remanufacturing programs, has aimed for zero waste discharge and has achieved 90% reuse and recycling (Environment Protection Authority 2002).

Based on these data, it is evident that many companies have realised that reverse logistics, particularly remanufacturing, is an important competitive and strategic component of their business mission. Indeed, the use of reverse logistics in the business sector is increasing not only because of the implementation of more stringent environmental regulations, but also for competitive reasons. The results of a survey involving 1,200 logistics managers and more than 150 managers with reverse logistics responsibilities in the US found that 65% of companies believe that returns management is an important strategic tool for their business (Rogers & Tibben-Lembke 2001). This increasing pressure to improve the market competitiveness of companies through the reverse logistics process has pushed researchers to analyse, model and explain why and how reverse logistics can lead to economic and environmental benefits. A number of studies describe the role of reverse logistics in economic and environmental activities during the product development process. In particular, several models have been developed to support managerial decision making and to optimise processes in different reverse logistics areas. The scope of these models is mostly to minimise costs and optimise profits through analysis of the parameters and variables as defined in the modelling method.

However, the characteristic of variability in quality, quantity and timing for returned products and the integration of the returns flow within the original forward supply chain makes reverse logistics activities, particularly remanufacturing, difficult to plan, control and manage (Guide & Wassenhove 2001). For this reason, systems not appropriate for dealing with returns could increase operating expenses. In a study by Guide (2000), 61.5% of the firms were found to have no control over the timing or quantity of returns. He discusses several characteristics of recoverable manufacturing systems that complicate production planning and points out that there is a significant lack of specific technologies and techniques for remanufacturing logistics. These specifically include: uncertainty in timing and quantity of returns; balancing returns with demands; disassembly of returned products; and materials recovery uncertainty—and are all factors that require considerable research. These characteristics could be addressed by focusing on several issues, such as methods (e.g. leasing, deposits) used to reduce uncertainty in timing and quantity of returns; forecasting models; aggregate production planning models that consider returns; and models that support material recovery planning and prediction based on the age and usage rate of products.

Production and inventory management requires appropriate control mechanisms to integrate the return flow of used products within the material planning for the forward flow (Fleischmann et al. 1997). This can vary for different reverse logistics situations. For example, for companies whose business is recycling returns are the only inventory resources for the forward production process and used products or materials are the only raw materials. Traditional inventory control methods might be satisfactory in these situations. The mechanism is different for remanufacturing or reuse, where used products are returned for introduction into the main production stream. In this case, returned goods consist of an additional inventory source to the usual inventory procured from outside. Moreover, this additional flow is not directly available to the manufacturer because of the unpredictable factors of quantity, time and quality of the products returned. Hence, inventory management can be made particularly complicated by remanufacturing activities since key information such as that related to on-hand inventory, lead time and yield are not clear in this process (Toktay, Wein & Zenios 2000).

For these reasons, in this research we model a production and inventory system in which production is integrated with remanufacturing activity. Several authors have conducted research into such a system. They have focused mainly on: production and remanufacturing lead times (Inderfurth & van der Laan 2001; Kiesmuller 2003; Kiesmuller & Minner 2003; van der Laan, Salomon & Dekker 1999); optimisation procedures for inventory levels and Economic Order Quantity (Kiesmuller & van der Laan 2001; Koh et al. 2002; Teunter 2001; van der Laan, Dekker & Salomon 1996; van der Laan et al. 1996); comparisons between pull and push strategies (van der Laan & Salomon 1997; van der Laan et al. 1999; van der Laan & Teunter 2006); and capacity planning (Georgiadis, Vlachos & Tagaras 2006; Kleber 2006; Vlachos, Georgiadis & Iakovou 2007). However, to our knowledge no other research studies such a system in which the returns process and the remanufacturing process are modelled and analysed in relation to the particular system variables involved in this research. Several inventory models for the remanufacturing process have been developed where returns are exogenous variables, without any or with only simple correlation between demand and returns. Many of these use simple assumptions regarding the return process such as the homogeneous Poisson Process for demand and/or return flow and returns independent of the demand (de Brito & Dekker 2003).

1.4 Methodology

The purpose of this research is to model the factors affecting a production and inventory system that combines returns and remanufacturing, and to evaluate effective control strategies in order to improve the performance of the system.

In this regard, the main steps adopted to conduct the modelling process initially involved an investigation of reverse logistics and closed loop supply modelling as reported in the literature. An investigation of previous models developed contributed to our research by increasing the knowledge required to conduct the modelling. Next, we focused on two processes involved in the production and inventory system for remanufacturing: the returns process and the remanufacturing process. The choice to focus the modelling on these two processes rather than to consider the entire system was made based on both on the quantity of variables, activities and policies to consider and on the number of assumptions made in order to simplify the system and its interpretation.

Regarding the modelling method, a system dynamics (SD) simulation modelling is adopted for this research. SD was introduced in the early 1960s by Jay Forrester (Forrester 1958, 1961) as a modelling and simulation methodology aimed at dealing with the dynamics and controllability of management systems (Coyle 1996). The purpose of the SD method is commonly to analyse how the dynamic behaviour patterns of system variables change in response to dynamic inputs. Controllability refers to the ‘control systems' (Coyle 1996) by which the policies employed, and applied in the system structure, control system behaviour over time. The objective of using SD is to identify strategies to improve system performance (Sterman 2000). For these reasons, SD has become a computer-aided method for analysing and solving complex problems, particularly in the area of policy analysis and design. It is applied in a number of fields, including: corporate planning and policy design; economic behaviour; public management; biological and medical modelling; energy and environmental studies; social science; dynamic decision making; complex non-linear dynamics; software engineering; and supply chain management (Angerhofer & Angelides 2000). The choice of using a simulation approach and in particular the SD approach, rather than other methods, in particular analytical approaches, was due to the recognition that the use of SD can help in modelling the entire system in which several policies and factors can be used for effective strategies evaluation in order to improve the performance of the system. Moreover, SD can handle the issues arising from those models in which dynamic forces and nonlinear relationships play a significant role.

In order to assess some of the research findings and to further validate the developed models, the methodological approach of this study involved case studies. These case studies gathered data from companies involved in reverse logistics and remanufacturing activities. The data were obtained both through interviews with company management and from existing literature. The companies involved were: (1) the Australian Mobile Telecommunications Association (AMTA), which through the MobileMuster program has commenced a national recycling program for mobile phones; (2) Fuji Xerox Australia, which is involved in remanufacturing of assemblies and sub-assemblies of printers and copiers; and (3) CEVA Logistics, which provides the materials handling services and the materials management services for the reverse supply chain of several Telstra products. The Fuji Xerox interviews were conducted at the Eco Manufacturing Centre located in Sydney, while for CEVA Logistics the interviews and the data collection took place at the CEVA Logistics Warehouse located in Melbourne.

1.5 Contributions

Following our purpose to model a production and inventory system for remanufacturing within the context of closed loop supply chains and to evaluate effective control strategies to improve system performance, this thesis makes several contributions in different research areas.

Firstly, as the current literature provides several inventory models for the remanufacturing process with no or only a simple correlation between demand and returns, in this research we model the returns process by incorporating the correlation of demand and returns. Such correlation is obtained through system variables which involve the usage of products and customer behaviour. Moreover, the remanufacturing process is modelled with particular consideration of variables in order to generate control mechanisms and policies for several system activities. We believe that our contribution in this area is to extend the literature with a more practical approach to product recovery and remanufacturing activity.

Secondly, in our research the problem of the uncertainty in timing and quantity of returns is specifically handled through identification of the relationships among variables in order to determine the quantities and times of return of used products with different product characteristics and for different industries. Our contribution in this area is to provide a tool and guidelines for determining the quantity and timing of used products returned by customers in order to reduce the uncertainty which negatively impacts on remanufacturing and traditional production planning.

Finally, in relation to the evaluations of effective control strategies aimed at improving the performance of the production and inventory system for remanufacturing, we offer several observations regarding efficiency in managing production/remanufacturing and inventory activities. Our contribution in this area is to provide an analysis of the effects of external factors and parameters on such a system which could inform a strategic decision making tool for production and inventory planning activities that involve a returns and remanufacturing process.

1.6 Outline of the Thesis

The remainder of this thesis is organised as follows:

- The literature review is presented in **Chapter 2** which outlines the current state of knowledge regarding reverse supply chain processes and SD simulation modelling. The modelling approaches applied by previous researchers in the field of reverse supply chain are also reviewed and examined.

- The research stages and the methods adopted are described in **Chapter 3**. The chapter explains the methodology used in this research through the description of the system under study and a discussion of the research approach. It also provides a detailed description of the steps involved in SD simulation modelling and an illustration and presentation of the case studies used in this research.

- The first SD simulation model of a production and inventory system for remanufacturing that focuses on the returns process is developed in **Chapter 4**. The main factors as well as the relationships among these factors that affect the behaviour of the system are identified and modelled following the primary steps of the SD simulation modelling approach. After validation of the model, simulation of scenarios based on the main factors that impact the returns process is conducted to investigate and evaluate effective control strategies for system performance improvement. In addition, data and information collected from AMTA and Fuji Xerox Australia are employed to assess the research findings.

- The second SD simulation model of the same system is developed in **Chapter 5**. The chapter explains the reasons why several assumptions are relaxed in order to remodel the remanufacturing process. Although the SD simulation modelling steps outlined in this chapter are similar to those used in the previous chapter, different factors and policies, obtained through analysis of the relationships among these factors, are now considered in the modelling process and for the simulation analysis. Data and information collected from CEVA Logistics are employed to assess the research findings and the robustness of the model.

- **Chapter 6** presents the conclusion in which a summary of the research findings and their contribution to the field are outlined. In addition, this chapter discusses the limitations of this research and suggestions for future research.

The thesis also contains two appendices:

- **Appendix A** contains the lists of variables used to model the production and inventory system with remanufacturing, both for the analysis of the returns process and analysis of the remanufacturing process.

- **Appendix B** contains the list of the orders and returns quantities of a particular product (emergency temporary phones) collected from CEVA Logistics on a time horizon of 60 weeks and across different Australian states.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides an overview of reverse supply chain processes and critically discusses previous research in this field. The aim is to develop a theoretical basis for addressing the research topic of the present thesis. The challenge is to identify the literature that informs this research topic, as well as possible gaps in the literature, and to address these gaps in the present study.

Reverse logistics and closed loop supply chain activities are the main research areas covered in this literature review, and an outline of the economic and social role of these activities is provided, including their advantages and limitations. Several examples of closed loop supply chains are outlined. The chapter also presents a discussion and analysis of the modelling approaches applied in previous studies in this field, and the main factors identified that particularly affect closed loop supply chains.

The system dynamics (SD) simulation modelling approach is also investigated during the review stage. In particular, an introduction of SD modelling is presented and SD modelling approaches for closed loop supply chain and traditional supply chain management systems reviewed with the aim of building the knowledge regarding the application of such methods in these two areas.

2.2 Reverse Logistics and Closed Loop Supply Chain

Reverse logistics (RL) and closed loop supply chain (CLSC) activities are both applied in returns management. The latter represents the supply chain management process by which activities associated with returns are managed within a firm and across the key actors of the supply chain (Lambert 2008). These two activities, as mentioned in Sections 1.1.1 and 1.1.2, employ reuse, remanufacturing and recycling methods to recapture value from product returns. However, a conceptual differentiation exists between RL and CLSC. CLSC refers to a complete supply chain process in which the reverse supply chain is usually tracked and controlled by the same organisation that supports the forward supply chain operations (Blumberg 2005). Closed loop supply chains generate an integrated system between forward and reverse logistics activities for which a strategic plan for distribution and collection, inventory control and production is required. In particular, traditional activities such as collection and distribution planning, inventory control and production planning have to be scheduled and planned to account for a returns flow. In contrast, RL can be represented by open loops as the reverse supply chain works independently from the original forward supply chain. However, both RL and CLSC activities can represent a company strategy to achieve economic and environmental benefits for the business through the reuse, remanufacturing and recycling of returns.

Returns have a real product value, and the reuse, refurbishment and resale of returned products or material represent a real economic opportunity (Blumberg 2005). In general, returns can be classified into three major areas: manufacturing, distribution and market returns (de Brito, Dekker & Flapper 2004). The first two areas are related to the process of manufacturing and distribution such as returns from a surplus of raw material and quality control as well as product recalls and business-to-business (B2B) commercial returns. The third area involves the users of products, and warranties, end of product use, and end of life returns. In terms of distribution and marked returns, returns can be: products that have failed, but can be repaired or reused; products that are obsolete or at the end of their leasing life, but still have value; unwanted and unsold products on retailers' shelves; and products that have been recalled and parts/sub-assemblies created from 'pull and replace' repairs in the field, which still have value.

Verma and Vhatkar (2005) outline a list of industries in which reverse logistics and closed loop supply chain activities could play a considerable role. Beverage industries, consumer goods industries and automobile industries need reverse logistics processes to collect and reuse empty bottles, fulfil the commitments of after-sale service and buy-back guarantee, respectively. Through a returns process, pharmaceuticals industries collect expired formulations and drugs for environmentally friendly disposal and publishing houses take back unsold volumes for recycling. Finally, heavy industries need to collect and reuse waste. The importance of considering reverse supply chains for these industries is crucial, considering that for some companies returns represent about 50% of sales (Prahinski & Kocabasoglu 2006).

The remainder of this section outlines some relevant background information on the roles of RL and CLSC and the difficulty of developing RL and CLSC systems. It also provides several examples of closed loop supply chains in the Australian context in relation to the reverse supply chain process.

2.2.1 Role of Reverse Logistics and Closed Loop Supply Chains

The introduction of new environmental legislation is strengthening the need to focus on RL and CLSC among logistics operators. While legislation introduced in Europe, North America and Japan encourages this awareness, many corporations have proactively taken measures in anticipation of evolving environmental performance requirements (Savaskan, Bhattacharya & Wassenhove 2004). Several examples of government regulations can be considered. In Japan any products purchased by the government must contain recycled materials and the European Union has issued a directive for producer responsibility to collect, process and recycle waste from both ‘white goods’ (e.g. refrigerators, washing machines and freezers) and ‘brown goods’ (e.g. TVs and speakers) (Kulwiec 2006). In Europe, many countries have forced industry to develop collection and recycling systems in order to reduce waste. This has led to the issuing of several environmental regulations such as the EU Directive 2000/53/EC (Blanc, Fleuren & Krikke 2004) for responsibility in taking care of used products, the EU Directive 2002/96/EC and 2003/108/EC for electrical and electronic equipment, and the EU Directive 2002/525/EC for end-of-life vehicles (Tang, Grubbström & Zanoni 2007). In the United States, according to the US Environmental Protection Agency (EPA), the amount of waste generated in the country has increased from 88 million tons in the 1960s to 196 million tons in 1990 alone. Consequently companies need to develop techniques for product recovery and waste management (Gungor & Grupta 1999). Furthermore, hundreds of environmental laws and regulations for recycling operations and responsibility for packaging recovery have been developed (Kulwiec 2006). Local governments in North America promote the reduction of landfill use, which is the main environmental driver for non-toxic solid waste, pushing companies towards improvement of and innovation in manufacturing activities (Biehl, Prater & Realff 2007). This places an onus on manufacturing firms to use reverse logistics activities as a form of extended producer responsibility (EPR) which makes them responsible for their products throughout their life cycles (Klausner & Hendrickson 2000).

From the previous examples, it is evident that the development of the reverse logistics concept is in line with environmental concerns. The latter in turn are increasing awareness of the importance of RL and CLSC, and that solutions for protection of the environment such as reuse, remanufacturing and recycling have increased interest in this area, both in terms of research and practice (Sarkis, Meade & Talluri 2004). Reverse logistics processes comprise the return flow of products as well as recovery, recycling activities, repair, renovation, reprocessing and cannibalisation. Thus, the promotion of reverse logistics practices has both an economic and an environmental basis (Gonzalez-Torre, Adenso-Diaz & Artiba 2004). An apt example is waste disposal. Scarcity of landfill sites and the hazardous material contained in end-of-life products are environmental as well as economic problems. While the amount of solid waste is increasing, the availability of landfill sites is decreasing (Gungor & Grupta 1999). In the US these sites decreased from 18,000 in 1985 to 9,000 in 1989 and there are now stricter environmental laws prohibiting or restricting the dumping and burying of waste. At the same time, the cost of disposal is an important economic factor for companies. In Europe, disposal costs represent 2% of direct production costs of laser printers, 3% for cars and 12.5% for white goods (Ayres, Ferrer & Van Leynseele 1997). For this reason, companies are motivated to incorporate disposal costs in product prices and to design their products to enable the recapture of remaining value at the end of their lives (Klausner & Hendrickson 2000).

A reverse logistics process has a broader importance for a company's activities than solely to fulfil government regulations or environmental issues. The use of reverse logistics and closed loop supply chains is increasing in the business world not only because of legal restrictions but also for competitive reasons. The traditional approach of many companies towards returns has been simply to ignore them (Thierry et al. 1995). Their only objective for the supply chain was to minimise the costs of purchasing materials, production and distribution without taking into account remanufacturing, reuse, recycling and disposal requirements in order to optimise operational processes. Today, companies are recognising that reverse logistics processes could lead to increased opportunities for their business. Indeed, through reverse logistics and closed loop supply chain activities companies could fulfil the environmental responsibilities stipulated by government regulations and at the same time optimise operational processes. Such optimisation can be achieved by reducing operating expenses and improving the company image, through a reduced use of resources as well as improving the life-cycle performance of the product.

The economic benefits obtained through reverse logistics and closed loop supply chain activities are discussed below first, followed by an explanation of the role of such activities in resource reduction. Finally, we discuss their roles at each stage of the product life cycle.

2.2.1.1 Economic Benefits

Companies from across a range of industries are considering the benefits to be gained from products and goods at the end of the forward supply chain (Verma & Vhatkar 2005). The cost of remanufacturing, for example, is typically 40–60% of the cost of manufacturing and remanufactured products are of the same quality as new products, and sold with the same warranties (Mitra 2007). Moreover, customers have become more environmentally conscious, which has led in recent years to an increase to over US$2000 billion worth of environmentally friendly products globally on the market (Mitra 2007). This increasing consumer interest in environmentally friendly products has encouraged companies to innovate and to meet these needs and thereby improve their competitiveness. For instance, companies could achieve competitive differentiation by attracting environmentally conscious customers and using returns as a valuable source of components and materials. However, presenting a company image as environmentally friendly is not the only motivating factor. Many direct marketers offer generous return policies in a competitive system to improve customer service as the returns percentage on sales is increasing (Hess & Mayhew 1997). For example, return rates increased by about 10% in the early 1990s and in some merchandise categories this figure reached around 70%. The increasing trend of internet sales and E-commerce also raises return rates. In many countries, legislation allows E-commerce customers to return products even if they are in good condition and to receive a refund (Vlachos & Dekker 2003). In this case, the easier return process increases return flows, which in some industries are as high as 35% of the initial forward flow. This heightened interest in environmentally friendly products, coupled with increased return rates, places pressure on companies to adopt reverse logistics processes and reuse discarded products to enhance both their company image and their competitive advantage.

An efficient reverse supply chain brings many benefits to a company (Roy 2003). These include: (1) the reduction of operating costs through the recovery and reuse of products or components; (2) the reduction of disposal costs; (3) the improvement of distribution channels through a more efficient process for collecting obsolete, outdated or clearance items; (4) the fulfilment of environmental regulations; (5) a more efficient aftermarket; (6) customer service which has become a key competitive differentiator in many industries; (7) improvement in the value of the company brand through the recovery of products which will be used to benefit the community or for altruistic purposes.

However, the hidden benefits of RL processes are sometimes not taken into account. For example, there are four main hidden benefits that can be gained through an effective reverse logistics process (Mollenkopf & Closs 2005). Firstly, the replacement of unsold stock returned by retailers with new models maintains retail prices and avoids markdowns. New stock, constituted of new products at the point of sale, provide higher prices than old stock. In this way, it is also possible to capture any remaining value in the product—for example, through remanufacturing or secondary market sales. Secondly, the goodwill engendered among customers through adoption of reverse logistics processes and the proper disposal of products can build substantial customer loyalty through increasing the value of the company brand. A good example of this can be seen in Nike, which takes back used running shoes to build public basketball courts and running tracks as community actions. Cost reduction is the third major benefit. The reduced cost of operating and environmental compliance cost of goods sold (COGS) are not the only ones to consider. Customer service costs can also be reduced when the returns process is streamlined. Moreover, data on customers' reasons for returning goods can be used to improve the product, thereby reducing future returns. Finally, better management of the returns inventory can improve asset turnover. Returns management can help lower the inventory of revenue generating items and reduce the need to store items that do not generate revenue. In this way, an improvement in assets, in terms of the inventory and the facilities required to store it, is possible. However, it is vital to develop a good returns management process that includes better gatekeeping or point-of-entry management as part of the reverse logistics pipeline (Reverse Logistics Executive Council 2007a).

2.2.1.2 Resources Reduction

The growing recognition of the limited quantity of natural resources, which comprise the raw materials of production, energy, water, air supply and landfill sites, is pushing societies to employ corrective actions to create a sustainable world for future generations (Gungor & Grupta 1999). Resources reduction alongside the use of renewable energy can form part of such corrective actions, and RL and CLSC have an important role to play in resources reduction. This role is represented in Figure 2.1, which depicts a hierarchy among several activities in accordance with the capacity to recapture value from used products, to reduce production resources and to be environmentally friendly. The activities presented are typical reverse logistics processes adopted by companies to recover used products. However, all of these activities, except for landfill, recover value from used products, are environmentally friendly processes and use fewer resources to produce new products and energy. Through reuse, repair and refurbishing, it is possible to put on the market products made from renovated returns. Remanufacturing and recycling are processes that produce new products using parts and components from returns or by reprocessing used material. Incineration or similar disposal activities can generate energy out of waste or used products. Landfill is the only activity that does not generate added value for companies but rather imposes a heavy expense on each item. It is both an economic and an environmental problem due to the cost that companies must incur to dispose of waste. This cost is exacerbated by the growing shortage of land that can be used for this purpose and related environmental problems.

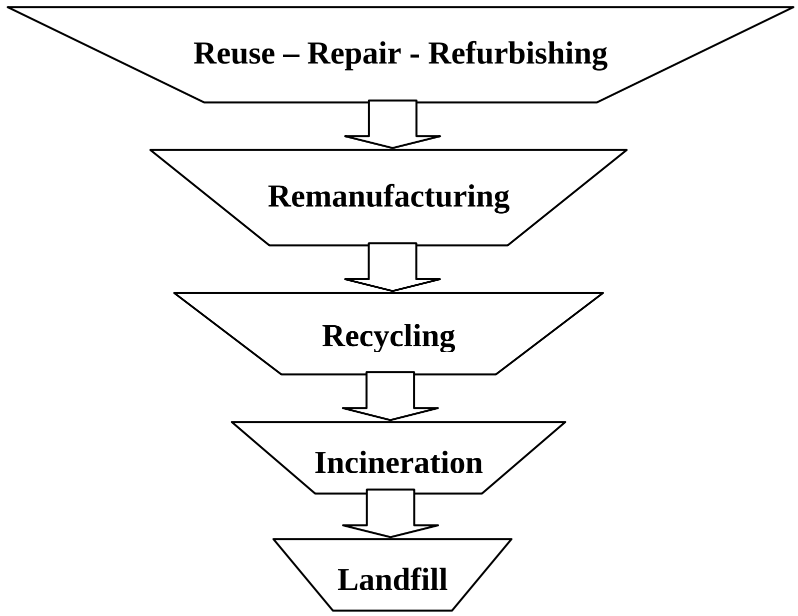


Figure 2.1: Resources reduction (adapted from Dekker et al.(2004))

2.2.1.3 Reverse Logistics Activities and Product Life Cycle

Product life cycle is a concept that describes the different sales phases of a product, which can be classified overall into introduction, growth, maturity or decline. Following this schema, it is possible to analyse the sales tendencies over the life cycle of a product. At the introduction stage sales grow slowly, which is followed by rapid and slow growth during the growth and maturity periods, respectively, and then a decrease during the decline period. Reverse logistics processes can extend this concept to show the tendency of the product returns life cycle for each of the same traditional sales phases (Tibben-Lembke 2002). The integration of the reverse logistics concept and one of the fundamental concepts within the manufacturing environment points out the critical role that this conceptualisation can play for understanding of a company's functional strategies.

Figure 2.2 represents a general product life cycle and a returns life cycle. The returns rate increases during all the phases in which product sales increase. This increase in returns is based on the reasons for which a product is returned: for example, damages and guarantees; expiry date; replacements; seasonality; and the end of life of the product to be disposed of or remanufactured are all factors driving product returns (Tibben-Lembke 2002). Thus, the sales volume affects the returns rate. Indeed, during the introduction period, products might be returned for any of the above-mentioned reasons but a low level of sales generates a low level of returns, which then increases during the growth and maturity phases. The decrease of product sales in the decline phase involves a drop of returns, but not as quickly as the returns follow the rate of previous sales, a pattern that continues after the end of the product life cycle.

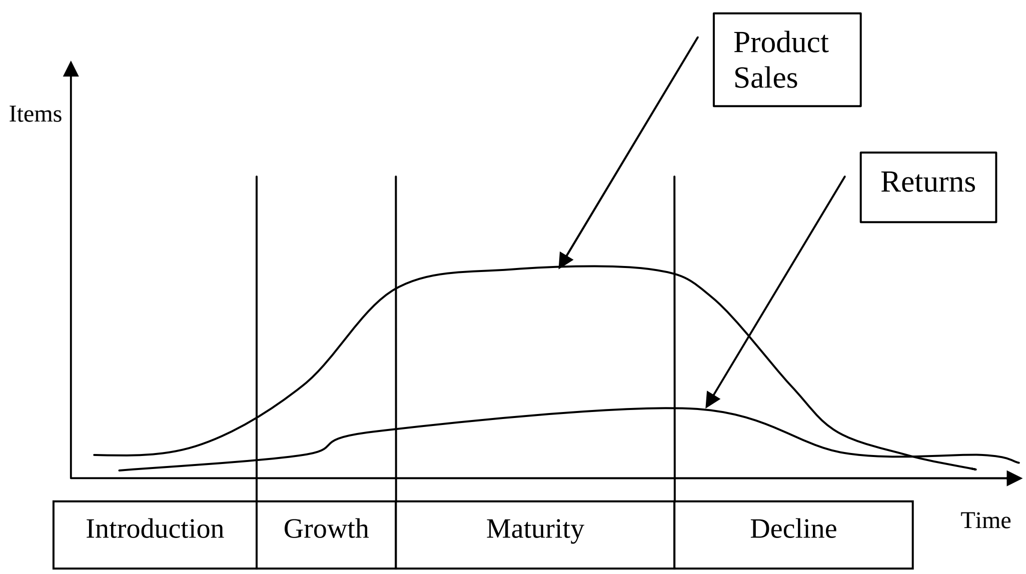


Figure 2.2: Product and returns life-cycle (adapted from Tibben-Lembke (2002))

The link between the product sales volume and the returns quantity raises the question of how reverse logistics activities can play an important role during the stages of the product life cycle. Analysis of the life cycle, not in terms of the function of the volume of sales but rather in terms of activities undertaken in the various processing stages for a product, may need to be incorporated into product recovery management to achieve environmental and economic benefits. Product life stages such as design, manufacturing, use and recovery or end of life necessitate environmentally friendly activities that address environmental issues, customer concerns and governmental regulations (Gungor & Grupta 1999). In particular, these activities are required at the end of the useful life of a product where reverse logistics and closed loop supply chain activities might resolve environmental problems such as waste disposal. However, reverse logistics and closed loop supply chain processes should not only be a concern at the final phase of the product life cycle, but also throughout the entire life of the product. Economic benefits can be obtained more readily if the product design at its development stage incorporates the reverse logistics concept to facilitate future disassembly or remanufacturing. In particular, if customers can purchase, use and later easily return products, this represents an enhanced customer service, and can also increases the returns rate and facilitates the collection, testing and selection of returns for reuse. Moreover, at the manufacturing stage, integration of production planning and inventory control with remanufacturing or product reuse activity can reduce operating expenses by reducing the need for resources and purchased materials. These are all examples that demonstrate how the concept of reverse logistics may be involved and integrated throughout the various phases of the product life cycle.

2.2.2 Barriers to Reverse Logistics and Closed Loop Supply Chain Systems

There are many barriers to the development of reverse logistics and closed loop supply chain systems. Based on the results of their survey, Rogers and Tibben-Lembke (2001) found that nearly 30% of managers with reverse logistics responsibilities thought that returns activities were not a priority for their firms. Specifically, it has not been possible for many firms to justify a large investment in developing reverse logistics systems and capabilities (Rogers & Tibben-Lembke 2001). It has been found that some companies do not look at the reverse supply chain as a business process (Guide, Harrison & Wassenhove 2003). They consider it to be more of a series of independent activities rather than a process that is integrated with the forward supply chain, following the concept of the closed loop supply chain. These companies often passively accept returns from the market and do not encourage their departments, whether sales, marketing or engineering, to design products that facilitate remanufacturing, disassembly and other reverse activities. This suggests that companies are uninformed of the potential economic benefits to be derived from the reverse logistics process. Indeed, Guide, Muyldermans and Wassenhove (2005), who worked on a reverse logistics project with Hewlett-Packard, state:

> *It* [Hewlett-Packard] *realizes that product returns represent a potential value stream and that it must approach the problem from a business-economics perspective, instead of making it an exercise in minimizing costs.*

Mollenkopf and Closs (2005) support the use of reverse logistics processes and seek to draw our attention to how companies are changing their views on this subject. They state that more companies are now viewing the returns process as a strategic activity—one that can enhance supply chain competitiveness over the long term. Moreover, they show how reverse logistics activities can have a positive financial impact on companies. The growth of product leasing and landfill costs, together with the new laws governing product disposal, have had a strong impact on company incomes. Landfill costs in the US, for example, are rising: landfill tipping fees have increased to an average of $33.70 per ton, and incinerator tipping fees to an average of $59.07 per ton. For these reasons '[b]usiness leaders are showing much more interest in reverse logistics' (Mollenkopf & Closs 2005).

Dealing effectively with returns can prove to be more expensive than anticipated, and companies with slim retail profit margins may feel they have too little to gain (Zieger 2003). Lund (1998), who developed seven criteria for product remanufacturability, states that two criteria to consider are the high levels of remaining value added on returned products and the relatively low cost of obtaining these products compared to their remaining value added. If the total cost incurred by returns process activities exceeds the total cost generated by the traditional forward supply chain, firms will have no financial incentive to implement a reverse logistics or closed loop supply chain process (Prahinski & Kocabasoglu 2006). Company costs could thus be increased by the adoption of reverse logistics activities such as remanufacturing and disposal (Inderfurth 2005). For this reason, a company objective is to optimise an integrated reverse and forward supply chain system to minimise the total costs and maximise benefits. For example, in remanufacturing systems, producers may be able to afford to include several reverse logistics activities such as more convenient returns collection, discounts to buy back used products and cash payments through cost savings generated from the remanufacturing activity (Klausner & Hendrickson 2000). A good example is seen in the model developed by Vlachos and Dekker (2003). In their closed loop supply chain system, the product has a unit purchase cost paid to the supplier, C, and a unit selling price P for which $P > C$ to have a positive profit. The surplus of unsold products can be sold in a secondary market at a unit value S, for which $S < C$. The returns process, which presents a recovery cost equal to C_r in order to ensure returns are in as-good-as-new condition, can meet customer demand through recovered products. This system should ensure positive expected profits if $C_r < P' - S$, in which P' is the new expected unit of revenue per satisfied customer order when utilising the recovery activity.

2.2.3 Examples of Closed Loop Supply Chains

Several examples of companies that have introduced closed loop supply chain projects into their systems are presented in the literature (Dekker et al. 2004). Such examples show how several activities and company systems are involved in a closed loop supply chain process.

Some of these examples are presented in the following sections in order to highlight the increasing interest in closed loop supply chain processes for different products and industries.

2.2.3.1 Kodak

Kodak decided to reuse some parts of its single-use camera. At the end of the life of the product some parts of these cameras, such as the circuit boards, have not deteriorated from use. Kodak has developed a closed loop supply chain process to recapture the value from those returned parts which can feed back into the production of remanufactured cameras. The detailed flow of this closed loop supply chain process reveals two key stages at the base of the system (Guide, Jayaraman & Linton 2003). The first stage entails the implementation of a new product design that facilitates the reuse and remanufacturing of parts and components through easier disassembly and assembly activities. The second stage involves a company service agreement between Kodak and photofinishers that the latter return used products, which represents an integrated system between the reverse and forward supply chains. In this way Kodak is in a position to determine and plan, for example, the best time to introduce new products onto the market which will make previous circuit boards obsolete, its collection policy, the procurement of new circuit boards, and the inventory management of new circuit boards. Through this program, Kodak has reused over 310 million cameras since 1990, with around 80% of reusable materials per product, and a return rate of more than 70% in the United States and almost

60% globally (Guide, Jayaraman & Linton 2003). However, one of the main factors of this closed loop supply chain process is the forecasting of the quantity and timing of returns. In particular, the returns flow of Kodak products is affected by uncertainty and unobservability regarding the timing of returns. Specifically, the period between the sale and the return of the product cannot be controlled by the company, so Kodak uses statistical models in an effort to reduce this uncertainty (Guide, Jayaraman & Linton 2003).

2.2.3.2 IBM

In the Americas, Europe, the Middle East, Africa and the Asia Pacific IBM has developed a product returns program, primarily for personal computers. This project aims to fulfil IBM's responsibility to the consumer market and to benefit from the repair and reuse of replaced components. IBM has established a business unit dedicated to the management of recovery, with 25 facilities steering repair, remanufacturing and recycling (with the involvement of third parties). The program involves several reverse logistics activities which organise the collection of product returns and disassembly/assembly activities in order to select the components for the repair, remanufacturing and recycling processes.

2.2.3.3 Volkswagen

Volkswagen uses returned products to remanufacture car parts, which are subsequently sold as spare parts. The main problem within this process is the excess of demand from the market which is not always matched by the supply of recovered parts, requiring additional production of new parts by Volkswagen. Moreover, the return flow poses some problems related to the uncertainty in the quantity and quality of returned parts. The reduction of this uncertainty is a fundamental activity within a closed loop supply chain process which, if not managed adequately, can lead to disposal due to excess products or non-remanufacturability.

2.2.3.4 Fuji Xerox

The revised planning of the manufacturing line implemented by Fuji Xerox is another good example of a closed loop supply chain. The assembly of new parts for photocopiers and commercial printers and the reassembly of refurbished parts are undertaken on the same assembly line. This integration involves the careful coordination of production and remanufacturing orders. Moreover, it requires careful coordination of the various production stages such as, for example, the disassembly of returned machines and the orders for refurbished parts.

Fuji Xerox in Europe has developed a reverse logistics program for all of the products they sell or lease (Guide, Jayaraman & Linton 2003). Returns are collected from the customers to be transferred to regional distribution centres for disassembly, testing and grading. Grading is based on several factors such as the overall condition and age of the machine; demand from manufacturing and service support for reused parts; and the recoverable inventory level. At this stage machines can be repaired, recycled or remanufactured through the replacement of parts and components. If remanufacturing is not economically suitable, parts and components that can be still reused are recovered from the machine to be included in a reused parts inventory. Then repaired and remanufactured products are distributed to the market through the original supply chain. One of the main competitive advantages obtained is through the company’s use of product lease agreements. This reduces the uncertainty of returns timing and quantity, facilitating easier planning and scheduling of the remanufacturing process. However, uncertainty is higher in relation to returns quality—as this depends on the intensity of use and age of the machines—which in turn increases the need for and complexity of testing and evaluation activities. Through its closed loop supply chain system, Fuji Xerox has achieved several economic benefits. In 1999 the company saved over US$76 million and in 1998 145 million pounds of waste from landfill. Moreover, the financial benefits of remanufacturing and the reduced use of raw material and energy has amounted to savings of several hundred million dollars per year, with a 90% rate of remanufacturable equipment (Guide, Jayaraman & Linton 2003).

2.2.4 Australian Context

In Australia, Johnson (2004) blames the negative attitudes prevalent in the Australian industry for the dearth of reverse supply chain processes. According to the author, the inadequate management of the return of goods is costing Australian business millions of dollars and potentially causing a whole range of problems for manufacturers. Johnson supports the potential value of returned products and the benefit that companies can gain by adopting a returns process, and at the same time criticises Australian companies for their low levels of interest in this area.

However, the Australian context also presents several examples of companies that are utilising reverse logistics and closed loop supply chain processes. Companies like Visy Industries and Cleanaway have adopted reverse logistics processes. Visy Recycling provides valuable recycling, waste and environmental services through the collection, sorting and remanufacturing of recyclable materials. Every year, Visy Recycling collects and processes more than 900,000 tonnes of paper and cardboard, about 450,000 tonnes of glass, more than 20,000 tonnes of plastic and about 5,000 tonnes of metals (Visy Recycling 2007). Other companies such as DHL Australia and CEVA Logistics Australia provide solutions as third-party logistics for reverse logistics activities. Their services include receiving, sorting, verifying and managing returned products (CEVA Logistics 2007; DHL Australia 2007). The most prominent case of company adoption of a closed loop supply chain in the Australian context, particularly in product remanufacturing, is Fuji Xerox Australia. According to the company's Managing Director, since the mid to late 1980s Fuji Xerox Australia has sold new products assembled using remanufactured parts and in the early 1990s the company commenced remanufacturing equipment in Australia (Lambert 2007). Today, the new equipment produced by Fuji Xerox contains up to 97% recyclable and reusable components, and the company routinely incorporates remanufactured components during original manufacture. Examples of Australian companies that use closed loop supply chain processes do not comprise the only evidence of the potential benefits of these processes. A simulation model of a reverse logistics network for collecting products at the end of their life to control their recovery or disposal in the Sydney metropolitan area has been developed by the University of New South Wales (Kara, Rugrungruang & Kaebernick 2007). The aim of their research was to provide a flexible model for addressing some of the problems associated with reverse logistics networks and to test the model on an existing collection system for white goods in Sydney.

2.3 Remanufacturing, Reuse and Recycling Modelling

The complexity of managing returns suggests the need to conduct a review of reverse logistics and closed loop supply chain modelling for the various applied methods and across the range of company areas involved. In this section, we present a review of the existing literature on remanufacturing, reuse and recycling modelling to identify the most influential models for these applied methods. The objective of this review is to develop a theoretical basis and to establish the research topic of the present thesis. The rationale for choosing the research topic are presented in Section 2.3.4

We first discuss the remanufacturing models, focusing on major topics such as: production planning and inventory control for product remanufacturing; remanufacturing network design; and costing/pricing in remanufacturing. We then discuss the reuse and recycling models.

2.3.1 Remanufacturing Models

The subject of remanufacturing systems has received increasing attention among researchers, and several authors have developed models for different industry contexts. In particular, we found that a number of these models focused on the integrated production and remanufacturing activities for production planning and inventory control systems.

Remanufacturing network design and costing/pricing for remanufacturing systems are also topics covered by the remanufacturing models. These areas have been investigated and developed mainly to optimise the total cost of the logistics network and to find the most suitable costing/pricing approach for remanufacturing systems.

2.3.1.1 Production and Inventory Control with Remanufacturing

The objective of inventory management in reverse logistics is to control external components orders and the internal components recovery process to ensure a specific service level and to minimise inventory costs. Additionally, in the case of remanufacturing, there is a need to determine whether it may actually be cheaper to overhaul a return than to produce or buy a new one (Fleischmann et al. 1997).

To clarify the terminology used in the models, Figure 2.3 shows a typical production and inventory system for remanufacturing. Returns are stored as recoverable inventory to be disposed of or remanufactured dependent on their quality or company inventory policy. Serviceable inventory, used to fulfil external demands, is fed by manufactured or remanufactured products or the procurement of new products. A remanufacturing system does not focus only on production and remanufacturing activities as analysis must be undertaken and decisions made in relation to inventory, operational and marketing activities also.

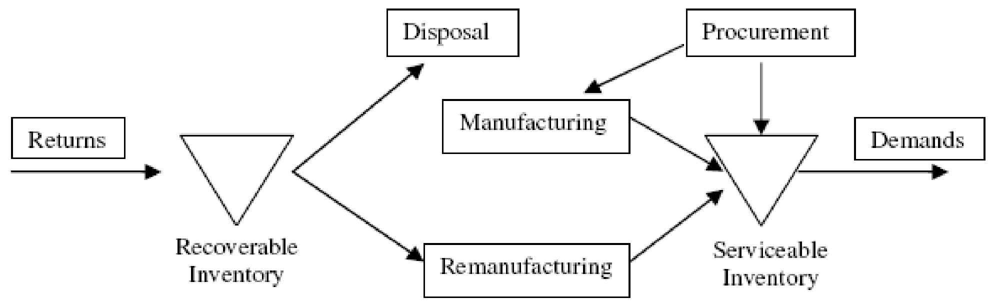


Figure 2.3: Typical production and inventory system for remanufacturing (adapted from Inderfurth & van der Laan (2001))

van der Laan, Dekker and Salomon developed an inventory control model in order to compare procurement and inventory control strategies and to determine an optimal approach based on cost minimisation (van der Laan, Dekker & Salomon 1996). The aim was to compare different procurement and inventory control strategies in order to find the best one, based on minimal costs, through testing in scenarios in which parameters are varied. A similar model was analysed by other researchers in order to find the optimal serviceable inventory level and procurement order quantity to minimise total inventory/production costs (van der Laan et al. 1996). Their study is similar to the procurement and inventory control strategy proposed by van der Laan, Dekker and Salomon (1996) in which the disposal of returns would depend only on the capacity of the remanufacturing facility, and the recoverable inventory level at which the returns are disposed of is not considered or is considered equal to infinity.

For each of these above-mentioned models an analysis of the variation of total costs was presented, given varying parameters in relation to particular returns rates. However, the procurement of new components for a remanufacturing system is examined more specifically by Toktay, Wein and Zenios (2000). They used a closed queuing network model of the remanufacture of single use cameras with the aim of developing an ordering policy and minimising procurement, inventory and lost sales costs. In their study, mathematical and statistical theory including Bayesian estimation and the expectation maximisation (EM) algorithm was used to estimate the parameters such as returns quantity.

In contrast to the models of van der Laan, Dekker and Salomon (1996) and van der Laan et al. (1996), van der Laan and Salomon developed a model of a production and inventory control system to explore more directly the push and pull inventory strategies for remanufacturing and disposal activities (van der Laan & Salomon 1997). According to these authors, a push strategy means that returns are pushed into the remanufacturing process as soon as the recoverable inventory level reaches a sufficient level. Conversely, in the pull strategy returns are pulled into the remanufacturing process only when a fixed sufficient quantity of recoverable inventory is available and at the same time the serviceable inventory actually requires more items to satisfy demand.

The main difference between the push and pull strategies relates to the timing of remanufacture and disposal. The remanufacturing batch in the push strategy is defined by an upper limit of recoverable inventory, since it occurs when the recoverable inventory reaches this limit. Disposal generally occurs after the remanufacturing batch is generated and depends on the upper limit of serviceable inventory. In the pull strategy the remanufacturing batch depends on both serviceable inventory levels and recoverable inventory quantities. Hence, it occurs when serviceable inventory reaches a fixed low level (or reorder point) and when a fixed quantity of recoverable inventory is available. Disposal occurs once the necessary recoverable inventory quantity is available. A comparison between the push and pull inventory strategies based on the optimal total system costs was undertaken using the model proposed by van der Laan and Salomon (1997) through an analytical approach. The results showed that the pull strategy is preferable to the push strategy if recoverable inventory levels are lower than serviceable inventory levels. This is generally because holding costs for serviceable inventory are higher than recoverable inventory holding costs and the pull strategy keeps remanufacturable items in the recoverable inventory.

The effects of lead time duration and variability on total cost in a hybrid manufacturing and remanufacturing system is the focus of another production and inventory control model (van der Laan, Salomon & Dekker 1999). Van der Laan, Salomon and Dekker use the same model and total system costs utilised by van der Laan and Salomon in their 1997 study, but without considering the disposal of recoverables as a possible inventory strategy. Their analysis revealed that an increase in manufacturing and remanufacturing lead time leads to an increase of total costs for both the push and pull inventory strategies. This could be explained by a common production operation management theory that stipulates that increasing the lead time, without changing the reorder point or order batch, increases the probability of backorders and consequently a larger amount of safety stock can be used. More specifically, the authors demonstrated that the increase in manufacturing lead time has a greater effect than does an equivalent increase in remanufacturing lead time. This was the result for a system in which remanufacturing orders have priority over manufacturing orders in order to feed the serviceable inventory, and in which manufacturing activity is used as a last resort to avoid backorders.

The findings of van der Laan, Salomon and Dekker (1999) also indicated that sometimes an increase in remanufacturing lead time leads to cost reductions if the remanufacturing lead time is smaller than the manufacturing lead time. In addition, the authors analysed the effects of lead time variability on total system costs using Bernoulli distributed lead times. Their results showed that for both push and pull strategies an increase in the variability of the manufacturing lead times leads to a decrease in total costs. Conversely, an increase in the variability of the remanufacturing lead times resulted in an increase in total system costs. Therefore, their results suggest that for such inventory systems a pull strategy is to be favoured over a push strategy as it lowers serviceable inventory holding costs. This is the case for systems in which the serviceable inventory holding cost is larger than the recoverable inventory holding cost, the lead time is considered stochastic and priority is given to remanufacturing over manufacturing in order to reduce recoverable inventory holding costs. The same result is valid for systems with large return rates (van der Laan & Salomon 1997).

Another model for a production and inventory system for remanufacturing was developed by Inderfurth and van der Laan (2001) with the aim of minimising total average long-run costs. In this model, the remanufacturing lead time is a decision variable and its variation can decrease total system costs. Specifically, for a push inventory strategy as defined by van der Laan, Salomon and Dekker (1999), the optimised costs can be obtained through fixed remanufacturing processing time and an effective remanufacturing lead time.

Adopting a different approach to that of Inderfurth and van der Laan (2001), Kiesmuller and van der Laan (2001) developed an inventory model in which the lead time is not a decision variable. In this model, the dependent relation between previous customer demands and future returns makes recovery probability the key variable. The objective of this model was to minimise the total relevant system costs generated by the average relevant costs for several periods across which the planning horizon of the model was divided. The relevant costs are procurement, backorder and inventory holding costs.

Another research model proposed by Kiesmuller and Minner (2003) was also based on the serviceable inventory level. This study focused on a production and inventory model in which the serviceable inventory is fed by production and remanufacturing activities without factoring in the procurement and disposal options or the push or pull strategies. Through a stochastic product recovery inventory system, the authors developed a model with a news vendor type approach. The objective was to find the optimal production and remanufacture levels for minimising the total inventory costs. The latter include the recoverable and serviceable inventory holding costs and the backorder penalty costs.

A similar model was developed by Kiesmuller (2003) based on a similar objective. Both studies (Kiesmuller 2003; Kiesmuller & Minner 2003) demonstrate through simulation analysis the total inventory cost deviations for several scenarios of remanufacturing and production lead times, by changing the value of the return rate; while Kiesmuller’s (2003) model also investigated push and pull inventory strategies. In contrast to the approach adopted by van der Laan and Salomon (1997) and van der Laan, Salomon and Dekker (1999), the two strategies (push and pull) were defined using a new approach in Kiesmuller's (2003) model, whereby inventory information related to production and remanufacturing decisions were considered. In the push strategy, all returned items are directly remanufactured without the need to store them and the production quantity must be defined. In this strategy, the production and inventory system need only account for the serviceable inventory as the storage of returns is not required. In contrast, in the pull strategy returns are remanufactured only as demand requires them; otherwise, they are stored in the recoverable inventory for later use when needed. In Kiesmuller's (2003) study, the author analyses the main factors within the pull strategy that determine the remanufactured quantity and the produced quantity to minimise total inventory costs. These factors are the production orders and remanufacturing orders up to a certain level. Moreover, the formula:

$$X(t) = I_S(t) + \sum_{i=1}^{L_P} p(t-i) + \sum_{i=1}^{L_R} u(t-i) \tag{1}$$

is used in the analysis and represents the serviceable inventory position at time t which determines the decision as to when to produce and/or remanufacture and the production/remanufacturing quantity. In the formula, the factor $I_S(t)$ represents the serviceable net stock on hand (stock on hand minus backorders) at the beginning of period t. The last two factors represent outstanding production and remanufacturing orders respectively, in which L_P and L_R are the production and remanufacturing lead times. In the analysis, the author considers both cases for a larger remanufacturing lead time ($L_R > L_P$) and a larger production lead time ($L_R < L_P$). For the first case, it was necessary to first decide on the production quantity, after which the remanufacturing quantity or orders can be determined. This consideration is required because of the faster pace of production than that of remanufacturing orders received in the serviceable inventory. The serviceable inventory position used to determine the remanufacturing decision is similar to that in the previous generic formula, except that the production order placed at time t which has to be included in the previous consideration. This order can be represented by the factor $i = 0$ in the formula:

$$X_u(t) = I_S(t) + \sum_{i=0}^{L_P} p(t-i) + \sum_{i=1}^{L_R} u(t-i) \qquad (2)$$

In contrast, the serviceable inventory position used for the production decision considers only the outstanding production and remanufacturing orders which will arrive in the serviceable inventory in the period until the shorter lead time. This last consideration can be represented by the formula:

$$X_P(t) = I_S(t) + \sum_{i=1}^{L_P} p(t-i) + \sum_{i=0}^{L_P} u(t-(L_R - L_P + i)) \qquad (3)$$

For the second case ($L_R < L_P$), the author not only considers the serviceable net stock on hand but also the recoverable inventory on hand $I_R(t)$. Indeed, in systems in which production lead time is larger, it is necessary to count on the remanufacturing activity as it generates faster orders for the serviceable inventory. Moreover, in this way it is possible to avoid additional recoverable holding costs (Kiesmuller & Minner 2003). Then, the serviceable inventory position used for the production decision is represented by the formula:

$$X_P(t) = I_S(t) + I_R(t) + \sum_{i=1}^{L_P} p(t-i) + \sum_{i=1}^{L_R} u(t-1) \qquad (4)$$

while, for the remanufacturing decision it is:

$$X_u(t) = I_S(t) + \sum_{i=0}^{L_R} p(t-(L_P - L_R + i)) + \sum_{i=1}^{L_R} u(t-i) \qquad (5)$$

A recent study on production planning and inventory control in remanufacturing engines for vehicles viewed planned lead time as a decision variable (Tang, Grubbström & Zanoni 2007). In this study a different approach was taken to that of Inderfurth and van der Laan (2001) and the previous inventory control models, as Tang, Grubbström and Zanoni's (2007) study analyses specific remanufacturing activities such as disassembly and reassembly without considering the recoverable or serviceable inventory process. The strategy used is known as 'make to order' (MTO) for which the disassembly activity and remanufacturing process occur after a customer order is received. Hence, demand is the driving factor of the system in which a pull rather than a push strategy is used as disassembled components from returned products are stored, in readiness for future demand. The objective of the model, under these conditions, is to minimise the sum of the total inventory holding and stockout costs. Through a simulation analysis these authors demonstrated the changes both in total system costs and in the decision variable, varying the probability that a component after disassembly is of an acceptable quality to be remanufactured or reassembled.

2.3.1.2 Remanufacturing Network Design

Production and inventory control models are not the only area examined in the remanufacturing systems literature. A 0–1 mixed integer programming model is presented in literature by Jayaraman, Guide and Srivastava (1999), which deals with certain activities within a remanufacturing system such as location of remanufacturing/distribution facilities; transhipment; and production and stocking of the optimal quantities of remanufactured products. The aim of this model (REVLOG) was to provide solutions and assist companies in decision making regarding location, production and stocking issues which affect remanufacturing environments. The objective of this model is to minimise the total cost of the logistics network developed for a remanufacturing system. Similarly, the optimal reverse logistics network design was developed for a business case study which involved the remanufacturing of copying machines (Krikke, van Harten & Schuur 1999). After a careful description of the reverse chain for this European case study company, the authors developed a mixed integer linear programming (MILP) model to find the optimal facility location network design, considering three network cases. In particular, in the study, the problem of the uncertainty of the returns rate was dealt with through scenario analysis based on returns quantity and differentiated return fees scheduled for the returns quality.

2.3.1.3 Costing and Pricing in Remanufacturing

An average cost (AC) inventory model has been developed in the literature to set the holding cost rates for remanufacturing systems (Teunter, van der Laan & Inderfurth 2000). Using this model, several methods for setting the possible holding cost rates were proposed and compared. The optimal method revealed a relationship between the holding cost for non-serviceable, remanufactured and manufactured items and the marginal cost for manufacturing and remanufacturing one item. Investigating the same topic, Teunter and van der Laan (2002) argue that the AC method for setting the holding cost rates would not be appropriate for models involving both remanufacturing and disposal activity. The authors assert that AC models are easier to analyse than the more appropriate approach (discounted cash flow (DCF) models); however, it is not clear how to apply some factors within the AC method such as discount rate and capital cost for models with remanufacturing and disposal.

In contrast to cost minimisation approaches, some economic models have focused on optimal acquisition price and optimal selling price for remanufactured products, such as that of Guide, Teunter and Wassenhove (2003). Using their model, these authors obtained some computational results for a cellular phone remanufacturing company. In this model, the return rate and the customer demand rate were based on the acquisition price for a return and the price at which remanufactured products are sold, respectively, following an open loop system. Similarly, but in a different setting, a pricing model aimed at maximising the revenue from the recovered products was developed by Mitra (2007). Based on the remanufacture of cellular phones, this linear programming pricing model, which included numerical examples and sensitivity analysis, maximised the expected revenue. The main differences between the last two models cited relate to the quantity, quality and timing of returns. Mitra (2007) considered a closed loop system case in which the remanufacturer is responsible for recovering the returns without having any control over the quantity, quality or timing of returns. Conversely, for Guide, Teunter and Wassenhove (2003), the acquisition price offered to retailers for the recovery of returns can be used to control such factors.

2.3.2 Reuse Models

One reverse logistics method is to reuse used products or components. Several kinds of products can be reused at the end of the forward supply chain, such as the physical distribution of returnable containers explored by Kroon and Vrijens (1995). These authors studied an open and closed loop system in which containers are used to carry products along the supply chain from the points of origin (senders) to the points of destination (recipients), which are later transported back to these same origins. Moreover, a case study of a large logistics service organisation in the Netherlands was used to develop an MILP quantitative model. The objective in this study was to minimise distribution costs, by defining several system factors such as the required number of containers; the appropriate number of container depots and their locations; and the appropriate service, distribution and collection fees. Another example, for a different product, involved a reverse logistics network design aimed at reusing liquefied petroleum gas (LPG) tanks as second-hand products after a degassing process, in a study conducted by Blanc, Fleuren and Krikke (2004). Both a mixed integer programming (MIP) model, to minimise the total cost and optimise the facility location allocation network, and a vehicle routing model, to estimate collection costs, were used in this study. The proposed system considered a combination of two strategies: a degassing process at one location and the same process at a limited number of locations visited by a mobile degassing facility. Research by Klausner, Grimm & Hendrickson (1998) on electric motors adopted another type of reuse model. These authors studied reuse decisions based on data recorded during the use stage of the product, through a novel circuit (electronic data log

[EDL]) which records the usage history of a product in order to assess its degradation at the time of product recovery. Their economic model compared the total cost of manufacturing new motors not equipped with an EDL with the total manufacturing cost with reused motors and EDL installed. The aim was to identify the recovery rate required for profitable reuse.

The reuse method, as is the case for remanufacturing, has also been explored through studies regarding inventory control and order quantity. A strategic optimal order quantity model, which incorporates a returns flow, was developed for products in the E-commerce industry by Vlachos and Dekker (2003). In this study, the optimisation of the order quantity was obtained through the maximisation of expected profit. Moreover, these authors used the ‘classic newsboy problem’ for a single period product, in which they considered returns flow. The newsboy or news vendor problem is a stochastic inventory replenishment problem in the field of operations research (Kalvelagen 2003). It provides the optimal order quantity that maximises the expected profit if only one order can be placed before the effective demand is known. The same problem is faced by a newspaper vendor who has to order a quantity of newspapers without knowing the number of buyers. Vlachos and Dekker (2003) extended the classical newsboy problem using a returns flow and by introducing new factors such as: collection cost per product, recovery cost to bring in returns in as-good-as-new condition, fixed recovery costs and revenue for reused products. Through a simulation analysis of their model, they proved that for large return rates the use of the standard newsboy model involves a profit loss. This result was compared using different recovery strategies such as: no reuse and sell all returns in a secondary market; reuse returns directly without any recovery; reuse returns involving a recovery cost only for the reusable returns (items returned before the end of the selling period); the previous strategy either considering or not considering fixed recovery costs; and reuse returns all subject to a recovery cost either with or without fixed recovery costs.

2.3.3 Recycling Models

A two-level location model for recycling sand from construction waste was proposed in the Netherlands by Barros, Dekker and Scholten (1998). In particular, these authors developed a MILP model to answer questions related to a sand recycling network, concerning for example: type and number of infrastructures to be installed; their location; and quantity of sand to be handled. This study looked at environmental laws established by the Dutch Government around restricting dumping and incinerating of waste and improving recycling processes. The model was aimed at minimising the total cost of the recycling network in an open loop system.

Several models have focused on the recycling of carpet materials. For example, a facility location allocation model was developed by Louwers et al. (1999). Their model, formulated through a linear programming (LP) approach, focused on the logistic network in order to design: the physical locations of the different activities involved, the capacities of the facilities and the transportation modes. The goal was to minimise the total logistics costs. A similar model was presented by Realff, Ammons and Newton (1999), in which, however, the facility location decisions were based on qualitative argument and not calculated (Louwers et al. 1999). Still in the carpet industry, Biehl, Prater and Realff (2007) modelled a reverse logistics system in order to fulfil the reduction target (40% by 2012) of carpet waste flows from landfills in the US. In contrast to Louwers et al. (1999), they sought to overcome more directly the uncertainty of returns using two different scenarios for carpet returns. Moreover, the authors, rather than optimise an existing system, developed a reverse logistics system to provide guidance regarding the designation of variables such as: number of collection centres, variability in collection volumes, forecasting and control systems on return rates. The results of their simulation analysis suggest the need to increase the number of collection centres, improve methods of reducing uncertainty on reverse flows, and invest in information technology systems to support the reverse logistics network.

Recycling activity and the associated costs can lead to an increase in company costs which in turn reduces the possible economic benefits of undertaking such an activity (Klausner & Hendrickson 2000). For this reason, Klausner and Hendrickson (2000) studied a combined remanufacturing and recycling system in order to evaluate the economic benefits obtained by the trade-off between the economic loss incurred from recycling and the profits obtained from the remanufacturing activity. They developed a profit model in order to establish such a reverse logistics system. The latter was applied to the remanufacturing and recycling of materials for power tools.

Recently, Pati, Vrat and Kumar (2008) analysed and formulated a mixed integer goal programming (MIGP) model for a paper recycling logistics system. The scope of their model was to consider economic, social and quality implications for the paper recycling industry and to address certain management issues related to the reverse distribution network. Their findings can inform decision making regarding the optimisation of reverse logistics costs, the optimisation of material flow in the reverse distribution network, and the quantity of collected returns to achieve environmental benefits.

2.3.4 Discussion

An exploration of the existing literature regarding remanufacturing, reuse and recycling modelling has been provided. Through this discussion we established the research topic of this thesis as the remanufacturing system, in particular the production and inventory system for remanufacturing. The rationale for this choice is explained below.

Through the review it was found that a larger number of remanufacturing models, particularly for production and inventory systems for remanufacturing, have been developed in the literature, compared to reuse and recycling models. We believe that this disparity is due to the intrinsic characteristics of the remanufacturing system in which the complex integration between the traditional forward and reverse supply chain activities has attracted several researchers to develop models for process optimisation within these systems. Moreover, this complex integration makes several company activities difficult to manage and plan in order to obtain economic benefits. For this reason, it is understandable that researchers are interested in selecting such a research topic in order to develop strategic management tools of interest to both the academic and private sectors.

Regarding the chosen research area, previous models have been developed mainly to optimise the total system cost. This optimisation has been obtained through strategies applied to the procurement activity, inventory (push and pull strategies) and remanufacturing/production lead times. However, these studies have neglected to consider several activities that can impact on the remanufacturing process. For example, we believe that collection and inspection activities should be included in the modelling of such systems as they affect the quantity of remanufacturable returns and disposal.

Another observation is that stochastic and deterministic analytical approaches have been used to develop mathematical models of the system. However, we believe that the use of a systems approach can help in modelling the entire system in which several policies and factors not previously considered can be used for effective strategies evaluation in order to improve the performance of the system. For example, company policies concerning the efficient flow of remanufacturable/remanufactured items throughout the various stages of the remanufacturing system as well as the use of the inventory coverage can be useful for this purpose.

2.4 Closed Loop Supply Chain Modelling

In this section, a review of the existing literature on closed loop supply chain modelling is presented. The selection of past developed models for review in which the system under study can be identified as a closed loop supply chain system was based on the strong relationship between remanufacturing and the closed loop supply chain. The integration between the reverse and the traditional forward supply chain activities leads to this relationship. Indeed, remanufacturing often leads to closed loop supply chain systems (Fleischmann et al. 1997).

In the sections below, following the approach of Fleishmann et al. (1997), we review and discuss closed loop supply chain modelling for the main company activities involved. These include collection and distribution planning, inventory control and production planning. This review is necessary in order to understand the integration between the reverse distribution network and forward distribution network; which factors complicate production planning and inventory control in remanufacturing; and how to share resources between reverse and forward activities.

2.4.1 Collection and Distribution Planning

Reverse distribution involves the collection and transportation of returns (Fleischmann et al. 1997). Reverse distribution can take place through the original forward channel, through a separate reverse channel or through combinations of the forward and the reverse channels. Determining which approach should be used is the first issue that needs to be resolved. Often the reverse distribution activities such as collection involve the same actors engaged in the forward distribution process—for example, suppliers, manufacturers, distributors and consumers (Gungor & Grupta 1999). For this reason, the complexity of integrating the reverse and the forward logistics activities for each of these actors leads to the need to model the reverse and forward distributions independently. However, this approach can be appropriate for a reverse logistics process that works independently of the forward supply process, as an open loop system, which does not therefore need to be integrated with the forward distribution channel. For example, recycling generally uses an independent reverse channel. Conversely, remanufacturing necessitates a closed loop supply process with closer integration of the forward and reverse flows (Fleischmann et al. 1997).

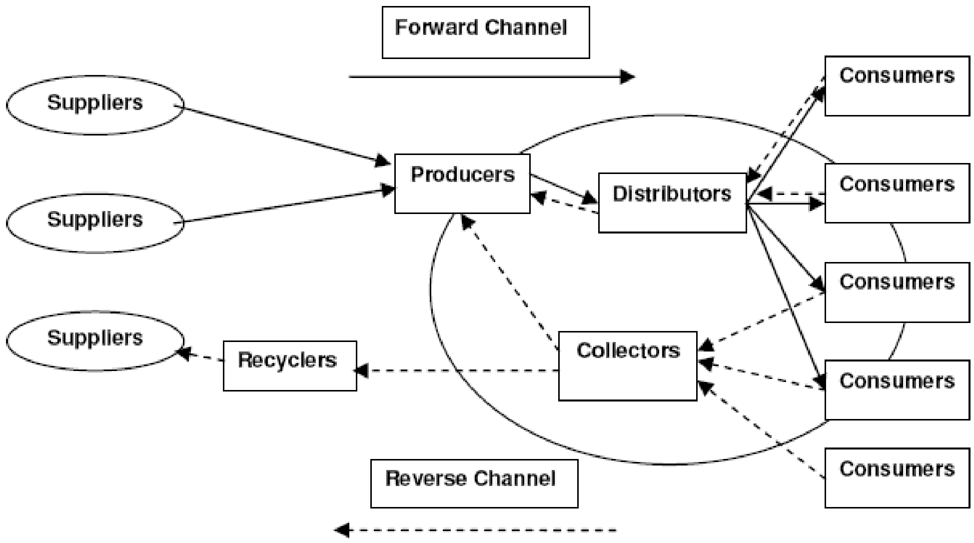


Figure 2.4: Framework of the reverse distribution (adapted from Fleischmann et al.(1997))

Figure 2.4 shows the different approaches to planning for reverse distribution. As shown in Figure 2.4, it is possible to observe, for example, the case of a closed loop supply chain for remanufacturing (the circle). Goods, from the producers through the distributors, reach the consumers following the forward channel and then returns from the consumers through the collectors, reach the producers following the reverse channel. In a different way, for recycling returns follow a reverse channel independently of the forward or original channel.

The issues related to the development of a reverse distribution channel can be the identification of reverse activities, such as pickup, collection, sorting, testing and repairing, and the allocation of these activities to the appropriate actors (Ferguson & Browne 2001). Several models of reverse distribution and the related issues are presented in the literature. These are generally derived from modifications of forward distribution channel models since the characteristics of the reverse distribution network—such as many sources to few demand points or uncertainty in terms of quantity and quality of returned products—contrast with the traditional distribution models and increase the level of uncertainty in a reverse logistics network planning (Fleischmann et al. 1997). The most widespread modelling approach to logistics network design problems adapted to a reverse logistics context is based on mixed integer linear programming (MILP) (Dekker et al. 2004).

Fleishmann et al. (2001) modelled a generic logistics network with a closed loop supply chain process. They demonstrated how the impact of product recovery on the logistics network depends on the context and the factors that lead to the efficient implementation or integration of product recovery in an existing forward distribution network. Similarly, a reverse channel structure for the collection of returns was modelled by Savaskan, Bhattacharya and Van Wassenhove (2004). Investigating three collection options for a manufacturer, they pointed out how the suitability of closed loop supply chains depends on the cost structures of the collection agents.

Also focusing on the collection activity, Beamon and Fernandez (2004) proposed a multi-period integer programming model to address the location problem of warehouses and collection centres for the remanufacture of used products. The main objective of their research was focused on the decision over the number and location of collection, recovery centres and warehouses to design a product recovery network that minimises investment and operational costs.

Recent research also shows a strong link between efficient closed loop supply chain processes and the number and location of initial collection points and a centralised return centre. A nonlinear programming model and a genetic algorithm have been proposed by Min, Ko and Ko (2006) to determine the right number and location for initial collection points to minimise the time required to hold returned products and to minimise costs of transshipment between them and return centres.

Lu and Bostel (2007) focused on the remanufacturing network and proposed a model in which they consider an interaction between forward and reverse flow. Salema, Barbosa-Povoa and Novais (2007) extended on this generic model, taking into account three other important characteristics for a reverse logistics network: limited production/storage capacity, multi-product production, and uncertainty in demand/return flow.

Uncertainty is the characteristic within product recovery networks that has driven authors to adopt a stochastic approach instead of using deterministic location models. Stochastic models were applied to a case study by Listes and Dekker (2005) on reusing sand from demolition waste in the Netherlands. These authors indicated how the deterministic location model may be extended using stochastic programming techniques. Previously, and based on the same case study, Barros, Dekker and Scholten (1998) investigated uncertainty using scenario analysis. Related to this group of work, Listes (2007) presented a generic stochastic location model for the design of closed loop networks which considered both the supply and the return channel. In this paper an alternative research direction to quantitative modelling was presented as a means of dealing with uncertainty in product recovery network design. A stochastic programming approach was used to manage the uncertainty in the quantity of demand and returns at the markets.

2.4.2 Inventory Control

Appropriate control mechanisms are required to integrate the return flow of used products with the material planning for the forward flow (Fleischmann et al. 1997). Figure 2.5 shows how returns of used products, after a recovery process, are added to the serviceable inventory together with outside procurement or production. The difficulty in this context is that return flows are often characterised by considerable uncertainty regarding time and quantity (de Brito & Van der Laan 2003).

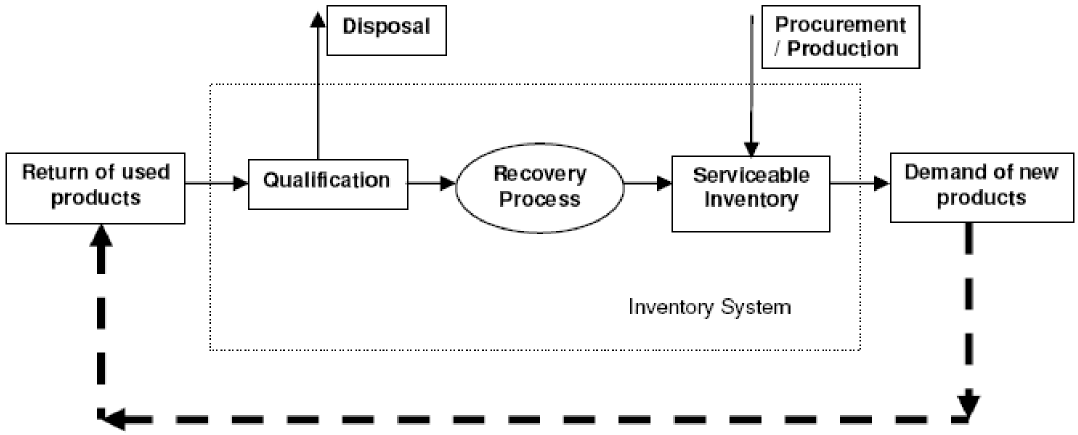


Figure 2.5: Framework of the inventory management with returns (adapted from Fleischmann et al.(1997))

Fleishmann et al. (1997) and de Brito and Dekker (2003) show how inventory control models with return flows can be distinguished between deterministic models and stochastic models. In deterministic modelling the information presented in Figure 2.5, particularly for demands and returns, is assumed to be known with certainty. This is not the way demands and returns are treated in stochastic modelling, where they are assumed to be probabilistic.

In the inventory control literature, a deterministic inventory model for the reparable inventory system was developed by Schrady (1967) in order to determine the optimal procurement and repair quantities. Several studies have proposed inventory control models for hybrid production systems within manufacturing and recovery. Van der Laan at al. (1999) explored the major issues in production planning and inventory control for this subject. In particular, they compared traditional manufacturing processes with remanufacturing systems, analysed push and pull control strategies, and considered the effects of remanufacturing on inventory management. A generalised version of the model proposed by Schrady (1967) was presented by Teunter (2001), who investigated the use of a deterministic economic order quantity (EOQ) model of an inventory system with returns. This model included consideration of general policies as an alternation between manufacturing and recovery batches, variations in the disposal rate and different holding cost rates for manufactured and recovered items. On the same topic, Koh at al. (2002) proposed a deterministic model for an inventory system in which the demand is satisfied by recovered products and newly purchased products. They used a joint EOQ and economic production quantity (EPQ) model in which, in contrast to Teunter (2001), one setup/batch for recovery and many orders for new purchased products, or vice versa, were considered simultaneously.

2.4.3 Production Planning

The last area of investigation for closed loop supply chain modelling was production planning. The kind of planning problems and the adequacy of traditional production planning activities depend on the type of reverse logistics process considered (Fleischmann et al. 1997).

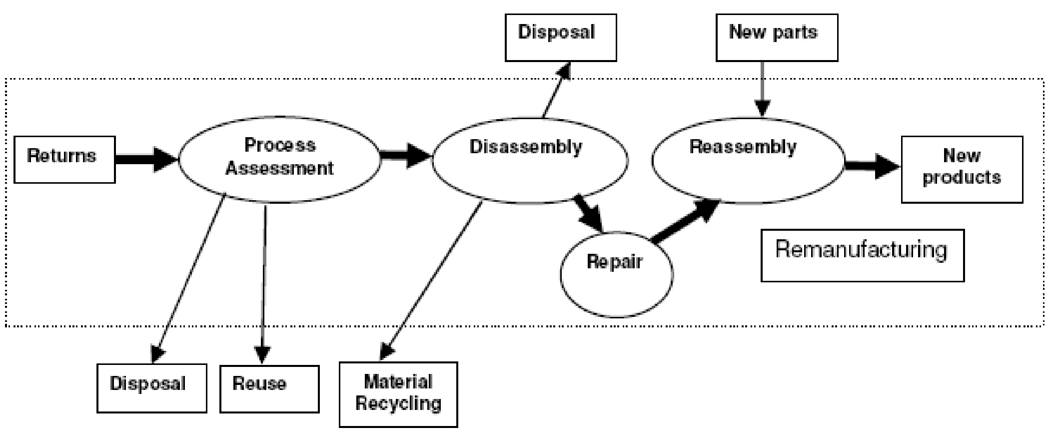


Figure 2.6: Framework of the production planning with returns (adapted from Fleischmann et al.(1997))

Products that will be simply reused do not constitute additions or changes to the traditional production process as returns are not involved in production activities. In recycling, returned products and materials are involved in production as they have to be transformed into raw material. However, these activities can be considered to be akin to a standard production process. The situation is different for remanufacturing, where activities like disassembly, repair and reassembly with new parts to create a new product generate more complexity in the process. This is shown in Figure 2.6, which represents a simple framework for production planning with returns.

The key questions in this context relate to determining the resources to be shared between manufacturing and remanufacturing and identifying the factors that complicate production planning and control in the remanufacturing of items created by both sources, internal production of incomplete parts and external returns of used products (RevLog 2007). One of the objectives is to balance and coordinate the return of items from consumers with production demand for remanufactured items, in order to maximise profits (Guide 2000). The primary reason for this complication is the uncertainty around the quality, quantity and timing of returns that will become raw material for the production process (Jayaraman 2006). For example, recovery uncertainty reflects that the different condition and number of returns involves different applications, and that returns could be remanufactured, used for spares, sold to a secondary market or recycled (Guide 2000). Standard activities in production planning such as materials planning, capacity planning and scheduling, and inventory management are therefore difficult to manage, and require investments in materials, equipment and labour to effectively plan, coordinate, control and manage operations.

In the remanufacturing industries modifications to the traditional material requirements planning (MRP) system are regularly employed (Dekker et al. 2004; Fleischmann et al. 1997). In particular, the bill of material (BOM) (a listing of the components with their description and quantity of each required to manufacture a product) must be extended to include multiple supply sources—one of which is the returned goods.

Studying production planning that incorporates product returns, Clegg, Williams and Uzsoy (1995) developed a linear programming model of a production system that incorporates remanufacturing and reuse operations. Their aim was to examine the effects of changes in the main model parameters and to guide company decision making regarding the system activities involved in order to maximise profits. Another linear programming approach, an MIP model, was presented by Teunter et al. (2000). These authors reported a case study of a German pharmaceutical company which uses a closed loop supply chain process to enhance its economic benefits, develop an environmentally friendly image and abide by legal requirements. This process involves the reuse of products and materials, which can complicate production planning activities. Specifically, the reuse of products extends and transforms the original bill of material which has rendered impossible the use of standard planning methods such as MRP and has pushed the company to develop an MIP model to resolve the problem. The objective of the model was to find the production plan method which, through a decision support system, translates the bill of material into a linear programming formulation in order to minimise the sum of set-up and holding costs over the planning horizon.

A fully integrated material planning system that manages the demand and supply of materials in remanufacturing shops was developed by Ferrer and Whybark (2001). This system, based on material requirement planning logic, is an extension of the methods used previously by other authors, as, for example, it explicitly links the volume of returns and sales, does not necessitate the modification of the bill of material, and optimises the procedures used to meet the demand for parts and uses.

A deterministic model with dynamic demands and returns for the product recovery system was proposed by Kleber, Minner and Kiesmuller (2002). Their main objective was to develop a model that synchronises production and remanufacturing, considering different demand categories. This required that several factors be examined so as to determine whether returns should be stored, used for remanufacturing instantly or disposed of, with the aim of satisfying the different customer demand classes. Lourenço and Soto (2002) developed a model that considered the returns for a production plan at an aggregate level for a multiple factories environment. In this model, a number of alternatives scenarios were studied to solve several problems that arise when integrating used products into traditional production planning. In particular, the model incorporates uncertainty around the quantity and quality of the returned product, which affects production time and the quantity of purchased materials.

Uncertainty renders the deterministic approach in the reverse logistics context inadequate in many contexts (Inderfurth 2005). Inderfurth presented a basic model of a hybrid production and remanufacturing system in a stochastic environment, in order to demonstrate how uncertainties affect product recovery behaviour. Moreover, recovery fraction and cost parameters were considered unrelated in order to improve remanufacturing profitability. This improvement can be achieved through activities such as investing in product recovery technology or improving remanufacturing processes, in order to directly reduce the unit remanufacturing cost.

2.4.4 Discussion

One of the main problems in developing efficient closed loop supply chain systems in order to obtain economic benefits is the uncertainty around quantity, timing and quality of returns. This uncertainty increases the difficulty of integrating the activities between the forward and the reverse supply chains. For example, if the number and the timing of the returns cannot be quantified and scheduled before re-entering the forward supply chain, the planning of several company activities (e.g. collection, inventory control and production) is difficult to realise. Moreover, the variability in the quality of returns can generate unexpected costs and increase the costs themselves at the inspection stage.

The literature reviewed on closed loop supply chain modelling explicitly recognises this uncertainty to be a problem in this research area. Several models have been developed in which the uncertainty was dealt with through deterministic and stochastic approach, particularly in relation to the quantity and timing of returns. For example, the number of returns was defined as equal to the quantity of demands or equal to a probabilistic percentage of the demands. However, we believe that the uncertainty in the quantity and timing of returns can be managed through a modelling process that accounts for several factors (e.g. customer behaviour and company incentives for the recovery of used products) that affect the returns process.

Effective operations and activities planning in closed loop supply chain systems can be crucial to obtaining benefits in terms of costs and service level. Based on the literature review, particularly for inventory control and production planning, we found that several authors confronted this topic by developing models concerning changes to traditional operations management tools (e.g. EOQ, MRP and BOM). Such changes were developed to extend traditional operations management theory to include the use of returned products. Such approaches involve the problem of how to share resources between the reverse and forward activities: for example, how resources in terms of the amount of work (e.g. equipment and material, number of workers and machines and increased production facilities (Heizer & Render 2006)) are to be shared across the remanufacturing and production activities. The allocation of resources within a traditional production process is related to capacity planning activity (Heizer & Render 2006). For this reason, we believe that an analysis of shared capacity planning activity between remanufacturing and production is of value to the modelling of a closed loop supply chain system.

2.5 Factors Influencing the Closed Loop Supply Chain

The identification of the main factors influencing the returns process can help in understanding how to include uncertainty—particularly in terms of quantity and timing of returns—within a modelling process of closed loop supply chain systems. We believe that customer behaviour and the incentives developed by companies aimed at promoting the recovery of used products can play an important role in the returns process. According to Gooley (1998), how and what to communicate with customers about returns and instructions for the returns process constitute one of the primary considerations when starting a closed loop supply chain program. Gooley states that customers who are well informed about this activity could avoid inefficient operations and receive better customer service. Moreover, customers need to be informed that reprocessed products share the same quality and performance as new products. This could reduce the misconception that reused, remanufactured or recycled products are inferior to new ones. We also believe that these two factors can also play a role in forecasting the quantity and timing of returns.

In this section an investigation of the existing literature concerning the role of these factors in closed loop supply chains is provided. We first discuss some studies concerning the uncertainty in quantity and timing of returns in closed loop supply chains. We then discuss the role of customer behaviour and company incentives in the returns process.

2.5.1 Uncertainty in Quantity and Timing of Returns

Several factors which complicate the planning and management of closed loop supply chain activities have been identified and these are: (1) uncertainty surrounding the quantity and timing of returns; (2) the need to balance demands with returns; (3) disassembly of returns; (4) uncertainty in materials recovered from returns and their corresponding restrictions in production activities; (5) requirements for a reverse logistics network; and (6) highly variable processing times (Guide, Jayaraman & Linton 2003). These factors can differentiate the analysis and implementation of a returns system. For example, products, after sale, may be used and returned within a different period of time and in different quantities. For this reason, the timing and quantity of returns are uncertain and may depend on customer behaviours in using the products. This could affect the resource planning for methods and activities used by companies to collect, test and remanufacture returned products. Moreover, product complexity resulting from the range of constituent parts and components makes recovery and remanufacturing processes even more complex because of the number of activities that must be planned and controlled for each different part and component.

Companies have to deal with considerable uncertainties in relation to timing and quantity of returned products, in addition to uncertain demand from forward logistics (Inderfurth 2005). Moreover, the lack of accurate data, references and information on comparable systems generates uncertainty in estimations (Blanc, Fleuren & Krikke 2004). However, by undertaking particular activities, such as forecasting systems and product acquisition management, it is possible to reduce the uncertainty effect (Inderfurth 2005). Through a prediction of the returns flow it is possible for companies to plan strategic activities such as network design; procurement; capacity planning; collection and disposal management; production; and inventory at the operational level (Toktay, van der Laan & de Brito 2003).

The uncertainty around the timing of returns can differ for different companies as a function of the product characteristics and returns volume. Guide, Jayaraman and Linton (2003) demonstrated through three different case studies representing remanufacture to stock (RMTS), reassemble to order (RATO) and remanufacture to order (RMTO) how uncertainty on returns timing can change according to different returns volumes and product complexity. RMTS represents a system in which returns are remanufactured to be stored and pushed again later onto the market. Thus, it offers a high returns volume and low product complexity that renders problematic the predictability of returns timing. In contrast, RATO and RMTO, which represent more a pull system in which products are remanufactured on order, create a moderate to low returns volume and moderate to high product complexity, respectively. In this case, returns timing is more predictable as companies can track their products after sale through, for example, leasing or a project contract.

2.5.2 Customer Behaviour and Company Incentives that Influence the Returns Process

Several issues related to assessing an economically viable remanufacturing program can be found in the literature. For example, Ayres, Ferrer and Van Leynseele (1997) point out that the distribution system has to include sufficient return flows in terms of volume and variety of returned products. This is essential for a manufacturer to achieve economies of scale on diverse product lines. The quantity of returns is dependent on the incentives and agreements with customers offered by the manufacturer to increase the returns rate. The aim is to decide whether to buy back or charge customers for used products. For example, Rank-Xerox used to pay for returned products, recognising their value, while Siemens charges customers for this activity. One of the problems that obstructs return rates is the behaviour of consumers (Klausner, Grimm & Hendrickson 1998). Klausner, Grimm and Hendrickson revealed through a case study that consumers prefer to store rather than return still functioning products and the majority are not willing to pay for disposal. Their case study focused on the returns process for small electric devices used in the home.

If the return flows justify the presence of a distribution system another issue is to recognise and verify the existence of recoverable high-value components and materials (Ayres, Ferrer & Van Leynseele 1997). Disassembly, for example, fundamentally will be profitable if the return value plus the savings of not requiring disposal is higher than the disassembly costs. However, these activities are only useful if customers are persuaded that they are not purchasing a product inferior in quality. Companies can employ different marketing tactics to successfully persuade their customers that this is so. Selling remanufactured products at a lower price or offering the same warranty as that for new products can function as an incentive for customers to buy a remanufactured model, so long as that these models are not inferior in quality.

The different categories of products that are recovered influence the possible forms of reuse, as these categories differ with respect to when and why items are returned

(Fleischmann et al. 1997). For example, packaging, which will generally be returned relatively quickly, is different to consumer goods which are mostly only returned at the end of their life cycle. For these reasons, the reverse process to recapture their value will require different actors and activities. Moreover, it is difficult to gain a thorough understanding of these activities, as they vary in complexity from scenario to scenario (Guide, Harrison & Wassenhove 2003). Thus, the differing characteristics of returns necessitate an appropriate reverse supply chain in order to optimise value recovery. Quinn (2005) proposed some useful questions that need to be addressed to manage an effective product returns process. He asserts that the three most critical factors to consider for managing returned goods are: ‘why products are being returned, how to optimize their returns management operations, and whether they should manage those operations internally or outsource them to a third party’. The author highlighted the necessity to consider certain variables in order to understand how a company might benefit from a closed loop supply chain project. These variables are ‘the percentage of a company’s products that are returned … to keep the “forward” and “reverse” operation separate … [and] to manage reverse logistics in-house or outsource it’.

Guide and Van Wassenhove (2001) suggested an interesting approach to managing products return that offers several operational benefits for remanufacturing. To reduce the effects of variability, in this approach returns are sorted, tested and graded in the reverse supply chain before entering the remanufacturing process. This approach can reduce the costs of the facility reserved for incoming used products, the quantity of used product inventory, disposal costs and variability of routings and processing times, thereby enabling an increase in productivity and cost effectiveness. These authors present an interesting case study in which this approach is applied to the remanufacturing process of mobile phone company ReCellular, Inc. This company achieved several benefits after initiating an agreement with mobile phone sellers to be responsible for ensuring that the used products were of an acceptable quality before sending to remanufacturing process. In this way, ReCellular, Inc. purchased used products already sorted, tested and graded, ensuring that these activities are undertaken prior to the reverse supply chain and thus reducing in-house costs. The approach used by Guide and Van Wassenhove (2001) is strongly related to the research of Blackburn et al. (2004). The latter authors found that the time sensitivity of product returns is significant to the design of an effective reverse supply chain. They argue that the financial benefits gained by implementing product postponement in the forward supply chain can be very useful in a reverse supply chain. This 'preponement' concept refers to a process that can avoid unnecessary processing expenses and provide faster recovery of returns with significant value. Their research shows that earlier activities, such as diagnosis and qualification of returns with consequent disposal or restock, in a reverse supply chain can maximise asset recovery by fast-tracking returns towards their final disposition and can therefore minimise the delay costs. For $1000 of product returns, about 45% of the asset value is lost during the return process, but an earlier diagnosis and discard would reduce the flow of units and would make processing easier and faster with a consequent reduction of lost asset value.

Another factor that can assist in optimising a returns system is proposed by Gentry (1999). This author states that it is a mistake in planning reverse logistics process to expect a distribution centre—which does not have the infrastructure to support both processes—to operate as a returns centre also. To eliminate costs and reduce cycle times, a centralised returns centre dedicated to managing the returns flow would be a better choice. To better curb the returns process activities costs, the time value of product returns must also be considered.

Returns system optimisation should not only focus on the phase of the return of the product but benefits can also be obtained if this has occurred during earlier stages. Gungor and Grupta (1999) developed a design for disassembly (DFD) as a method that provides the correct design specifications of a product to minimise the structural complexity by including a minimal number of parts and use of common material. This method leads to easier future disassembly of used products. The consequent benefits would be an optimisation in terms of costs and time for disassembly and the remanufacturing process. Moreover, an easier disassembly of the product can reduce the complexity of the activities of the return process. If the product, either at the end of its life or during the leasing period, is disassembled easily before commencing the return process, the manufacturer can handle the product components or parts and rather than the whole product along the reverse supply chain. This would lead to faster and earlier diagnosis, qualification and recovery of returns.

2.5.3 Discussion

Several studies have been identified in the existing literature which include theoretical and qualitative analysis of the effects of customer behaviour and in particular of company incentives used for the recovery of used products on the returns process. Some of these studies employ company case studies. The concern over these factors in this research field increases and supports our belief in using these factors in the modelling of the returns process. In particular, we believe that company incentives for the recovery of used products (e.g. service agreements and sales contracts with retailers or customers) can enhance efficiency in the reverse supply chain (Blackburn et al. 2004; Guide & Wassenhove 2001) as well as being useful as a forecasting tool for the quantity and timing of returns. Moreover, increasing company incentives of course encourages customers to return used products.

Several forecasting methods for the returns rate will be reviewed in the following section. The objective is to enhance our knowledge in relation to the modelling that includes this factor in closed loop supply chains.

2.6 Forecasting Returns Rate

The returns rate is one of the main factors afflicted by uncertainty in closed loop supply chain systems, particularly in production planning for remanufacturing activities.

Usually, returns are estimated either as a function of past sales/demands or they are considered independent of the sales process (Toktay, Wein & Zenios 2000). In the case of an independent relation between the two, a simple example is provided by Kiesmuller and Minner (2003). They assume returns to be independent of demand history and both are represented by a cumulative distribution function F_R and F_D respectively, with an expected value for returns equal to μ_R and a value for demands equal to μ_D. The returns rate is calculated as the ratio μ_R / μ_D.

Four different forecasting methods for returns quantity were modelled by Kelle and Silver (1989). Their research was applied to reusable containers, but their approach can be generalised to cover various industries. The difference among these forecasting processes is represented by the amount of information available to forecast the returns rate. All of the methods use historical data based on past issues of products and observed returns and expected value of future demands in order to calculate expected returns based on the success return probability of demands. Similarly, Toktay, Wein and Zenios (2000) assumed a dependent relation between the return and demand processes to model return flows. They developed this relationship through a distributed lag model, considering only one of the informational structures regarding the traceability of the products on which their research was based.

Investigating the same topic but utilising a less complex analysis, Kiesmuller and van der Laan (2001) state that random future returns can depend on previous customer demand, particularly in the case of rented or leased products. They assumed a probability that the item is returned to the manufacturer in such condition that it can be remanufactured and not necessitate its disposal. Based on this probability they calculated the expected number of returns as a function of demand.

This research topic was explored by Toktay, van der Laan and de Brito (2003) through a review of data-driven methods for forecasting future return flows as a function of past sales. These authors forecasted future returns based on a range of information: past sales volumes, return probability and return delay distribution. They classified the forecast models present in the literature in terms of the knowledge of total sales and return volume for each period or the sales and return dates of each product.

Forecasting the returns rate could be useful to reduce uncertainty over the quantity of future returns, but sometimes this is not enough. In the closed loop supply chain system developed by Vlachos and Dekker (2003) only a part of the returned products are reused to fulfil new orders, based on the assumption of using only one selling period within the system. This renders not serviceable the returns recovered after or close to this period. The proportion of returns that arrives in time to be reused is referred to as the serviceable return rate by Vlachos and Dekker. The estimation of this factor depends on both the net demand and the collection-recovery time. The former is the demand minus the returns, while the latter is the time required to ensure the returned product is in as-good-as-new condition after collection/recovery activity for delivery to the customer.

2.7 System Dynamics

System dynamics (SD) is a methodology and computer simulation modelling technique used for understanding the dynamic behaviour of complex systems in order to analyse and solve complex problems with a focus on policy analysis and design. Originally developed by Professor Jay Forrester at the Massachusetts Institute of Technology in the 1950s, SD is currently being used for a wide range of applications in practice by academics, large companies, consulting agencies and government organisations (Taylor 2008). Forrester recognised that social systems can contain many nonlinear relationships and dynamic forces which render not feasible the use of analytical approaches to solving model equations. Therefore, he proposed the use of a simulation approach to analyse the dynamic behaviour of such systems (Angerhofer & Angelides 2000; Coyle 1996).

In the section below, first we introduce both the basic modes of behaviour in dynamic systems which arise from the feedback structure of the SD modelling and the SD modelling process. Then an investigation of several SD applications for supply chain management and closed loop supply chain systems is presented.

2.7.1 Modes of Behaviour in Dynamic Systems

The behaviour of a system arises from its structure which in SD is modelled through feedback loops; stocks (accumulations) and flows of material; and nonlinearities created by the interaction of the physical structure of the system with the decision-making processes acting within it (Sterman 2000). Therefore, SD posits a relationship between the structure and the behaviour of a system, modelling the latter through feedback structures. The basic modes of behaviour in dynamic systems are: exponential growth, goal seeking, S-shaped growth and oscillation. These are represented in Figure 2.7. Each of these modes of behaviour can arise from feedback structures (Sterman 2000). Specifically, exponential growth (Figure 2.7 (a)) can be generated by positive feedback structures or loops in which the system variables involved present an increasing growth process. Conversely, goal seeking (Figure 2.7 (b)) arises from negative feedback structures or loops in which the state of the system moves toward a goal. Oscillations (Figure 2.7 (d)) are generated by negative feedback structures in which the state of the system is compared to its goal and corrective actions create a fluctuation around this goal. Combinations of negative and positive feedback structures generate an S-shaped growth (Figure 2.7 (c)) in which an initial exponential growth is followed by a goal-seeking behaviour.

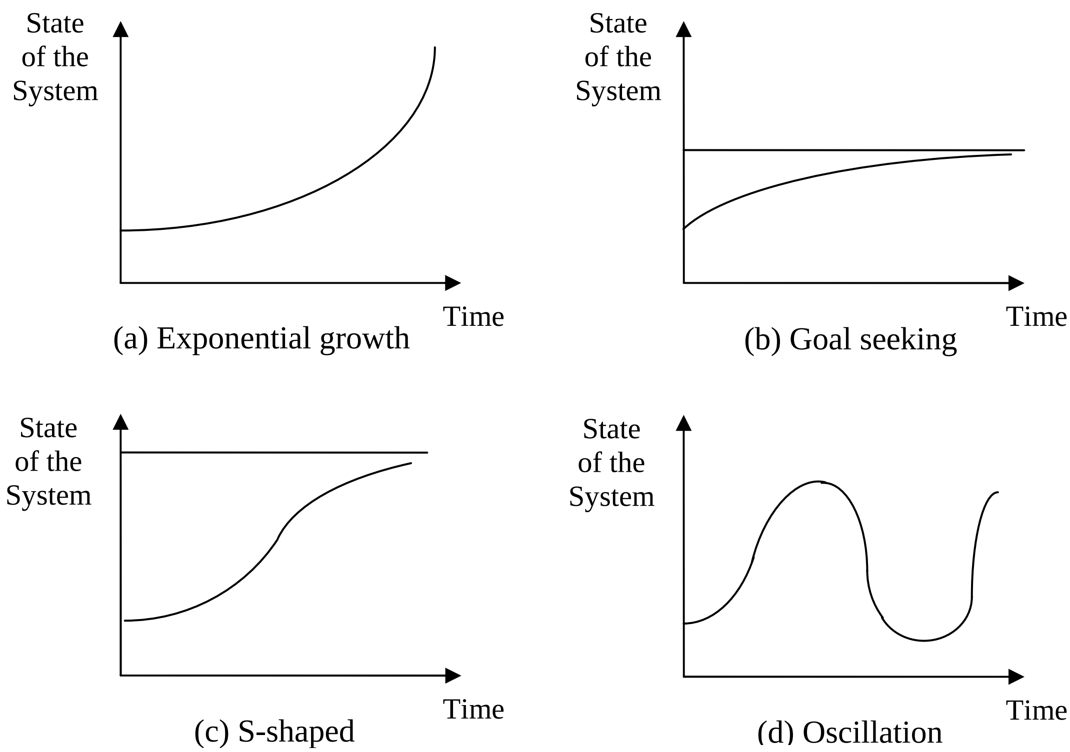


Figure 2.7: Modes of behaviour in dynamic systems (adapted from Kirkwood (1998))

2.7.2 System Dynamics Modelling Process

Various SD modelling approaches are published in the literature where authors usually define their own modelling process. For example, Figure 2.8 shows the process of SD (Figure 2.8 (a)) defined by Coyle (1996) and the modelling process (Figure 2.8 (b)) identified by Sterman (2000). Similarly, Maani & Cavana (2000) proposed five key steps in the development of SD simulation modelling: problem structuring; causal loop modelling; dynamic modelling; scenario planning; and modelling implementation and organisational learning. The number of steps and stages and their types vary in each approach; however, the path undertaken within an SD process can be generalised as following the iterative steps/stages of problem identification, model development, model validation, model simulation/output analysis and policy/strategy design and evaluation.

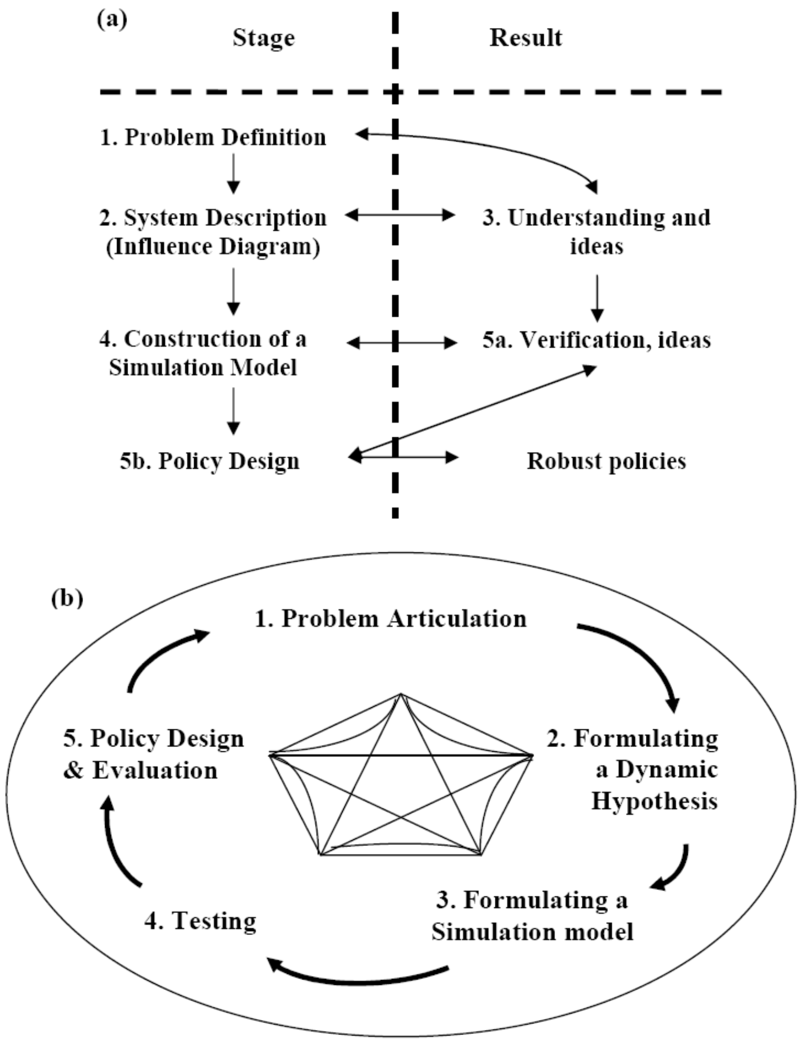


Figure 2.8: Processes of system dynamics (adapted from Coyle (1996) and Sterman (2000))

The stage of problem identification involves recognition of the problems and the purpose for which the model is developed. In this stage, the key system variables, the time horizon and the concepts to be considered should be identified in order to understand the problem and to design policies to solve it (Sterman 2000). Once the problem has been identified and the involved system variables and concepts have been defined over an appropriate time horizon, the second stage is characterised by the development of the model as a description of the system under study. SD includes several tools to help during this stage. In particular, the use of influence or Causal Loop Diagrams (CLDs) and Stock and Flow Diagrams (SFDs) provides respectively the qualitative and quantitative aspects of the SD modelling process. CLDs are flexible and useful tools for diagrammatic representation of the feedback structure of systems and the causal relationships among system variables, and include arrows from a cause to an effect (Sterman 2000). While the quantitative aspect of a model is obtained using variables in equations (Coyle 1996), the SFD provides mathematical equations that represent the relationships among the system variables. Once the model has been developed, a validation analysis has to be undertaken before it can be simulated. Such analysis is necessary in order to verify that the model behaves realistically and reproduces adequately the problem behaviour. Then the model can be simulated in order to evaluate and design policies and strategies through analysis of the dynamic behaviour of the system.

2.7.3 System Dynamics and Supply Chain Management

SD modelling involves several areas within supply chain management, such as: inventory decision and policy development; time compression; demand amplification; supply chain design and integration; and international supply chains (Angerhofer & Angelides 2000).

An SD approach for modelling a grocery supply chain system in the UK was adopted by Ge et al. (2004). In particular, they focused on the investigation of the demand amplification or bullwhip phenomenon for this particular supply chain system in which the performance of both the retailers and the suppliers can be affected by physical and informational delays. Changes in the demand rate from the retailer or the downstream chain necessitate changes in the order quantity and number of orders to the supplier or upstream chain. A responsive system, which reduces the delays caused by these changes along the supply chain, could improve performance by ensuring the optimal quantity of inventory and optimal number of orders and demand satisfaction, resulting in lower costs. The objective of their study was to analyse, through an SD model and simulation, the impact of information delay, demand forecast and information sharing on the performance of the system in order to identify the most effective company control policy. Based on the simulation analysis, the information sharing among different parts of the chain resulted in the most effective methods for performance improvement. Similarly to Ge et al.'s (2004) approach but looking at a different industry, Anderson, Fine and Parker (2000) presented an SD simulation model to explore the amplification phenomenon or bullwhip effect in the machine tool industry. Their findings suggested a cooperative relationship among partners along the supply chain. Such findings were obtained through an analysis of dynamic factors such as lead time, inventory, production, productivity and staffing. However, the findings also suggested the benefits of using long forecast rules in order to reduce order instability, as a strategy for those companies intent on supply chain design.

Zhang and Dilts's (2004) conducted research on the supply chain network organisation structure. Utilising an SD approach, different models of supply chain network structure were compared. The performance measurements looked at the impact of these models on the total costs and fill rate. Regarding the supply chain network, two supply chains were considered. These involved two suppliers and two plants, which were required to fulfil customer demand. The objective was to compare three different models of this supply chain network: (1) an independent model in which there is no interaction between the two supply chains; (2) a cooperative model; and (3) a competitive model between the two supply chains. Several variables were used to develop these SD models, including: inventory, work in process, backorder, expected order rate, and order record. The results of this analysis demonstrated the importance of cooperative model within a supply chain network.

Kleijnen and Smits (2003) reviewed various simulation approaches, which included SD simulation, in order to forecast through performance measurements the progress of strategic choices in supply chain management. Simulation can help to evaluate the changes in value of such performance measurements, quantifying their costs and benefits, so that dynamically the supply chain can be redesigned and alternative strategies can be chosen. Several performance measurements were considered using an appropriate tool in order to implement business strategy. This tool was the balance scorecard (BSC) which uses four types of performance measurements based on customers, internal processes, innovation and finance. This approach is the result of multiple measures used by company managers to evaluate performance processes such as the fill rate for customers; stock or work in process for internal processes; investments in information technology for innovation; and return on investment for finance. However, all of these factors are used to analyse current performance status only, which could also be analysed to identify future company strategies through dynamic simulation. According to Kleijnen and Smits (2003), SD could have a role in this activity through the dynamic simulation and comparison of performance measurements for different supply chain strategies, with the aim of eventually taking corrective actions in case of undesirable values.

2.7.4 System Dynamics and Closed Loop Supply Chain

Some researchers have been motivated to use an SD simulation modelling approach in the search for better strategies and policies for integrating the forward and reverse supply chains. However, there is still a lack of SD research into closed loop supply chains (Kumar & Yamaoka 2007).

An SD simulation tool was developed by Georgiadis and Vlachos (2004a) to analyse the dynamic behaviour and the influence of the various activities on the closed loop supply chain network. In particular, the objective of their research was to simulate a remanufacturing feedback loop to determine the effect of remanufacturing capacities and penalties on total costs under various scenarios. Penalties refer to the inappropriate collection and handling of used products imposed on companies by environmental legislation. It was found that total cost decreases when higher remanufacturing capacities are reached. In a similar study using SD by Georgiadis and Vlachos (2004b), the impact of environmental influences and remanufacturing capacity planning policies was simulated using a reverse logistics system. In this study, the effects of customer awareness of a company's green image on product demand and of environmental legislation on the collection rate of returns flow were analysed. The activities modelled in the system included: supply, production, distribution, usage, returns collection, inspection, remanufacturing and waste disposal.

A remanufacturing system was modelled in research by Georgiadis, Vlachos and Tagaras (2006) using SD to study the impact of product life cycles on planning optimal collection and remanufacturing capacities for several kinds of products with different life cycles and return characteristics. Two concepts were introduced in their study: 'residence time' and 'residence index'. Residence time is defined as the time the product stays with the customer before it is returned, while residence index represents the ratio of the average residence time over the length of the product life cycle. The residence index further represents the tendency of the product to stay and be used by the customer during its life cycle. It can be used to classify different products as to their suitability to be remanufactured. Their research focused mainly on the effect of the product life cycle on capacity planning.

Kumar and Yamaoka (2007) developed an SD model for the closed loop supply chain of the Japanese car industry. In their study, reuse, recycling and disposal activities were considered and in particular compared, for an expectation period of approximately 20 years, in order to evaluate the company policy of the manufacturers to export used cars to other countries. Through simulation analysis which used forecast data for the cars' consumption during the period analysed, the authors noticed a decrease in the volume of reused, recycled and disposed cars and an increase in exported used cars. This is to be understood by the lack of any tax on used car exports which makes exportation easier and cheaper for the manufacturers than recycling, reusing and disposing activities.

2.7.5 Discussion

The discussion of the existing literature regarding the topics presented in this section has reinforced our belief in using a systems approach, as mentioned in Section 2.3.4, and in particular an SD simulation modelling approach for addressing the research topic of the present thesis. Indeed, we believe that for a remanufacturing system, and in particular a production and inventory system for remanufacturing, nonlinear relationships and dynamic forces characterise the behaviour of the system. For this reason, a simulation approach is deemed appropriate for evaluating effective strategies for this particular system. Moreover, the SD modelling process, as described in Section 2.7.2, can be useful in order to define the several stages of our research process.

In relation to the investigation of several SD applications for supply chain management and in particular closed loop supply chain systems, we noticed that several studies have been successful in developing and simulating models of remanufacturing systems. The objective of these studies was mainly to analyse the effects of various environmental and operational activities on the defined measures of performance of the systems. The integration between the forward and the reverse supply chain activities was modelled with success in these studies. However, we believe that in terms of the operational management aspects, analysis, for example, of the shared capacity between production and remanufacturing and on lead times duration has been fairly limited. In particular, in terms of capacity planning, models have been developed that mainly analyse capacity expansion and contraction of collection and remanufacturing activities (Georgiadis & Vlachos 2004b; Georgiadis, Vlachos & Tagaras 2006). However, the implications of the constraints on capacity which must be shared between remanufacturing and production is another topic requiring further research (Kleber 2006).

While most of the previous models developed of remanufacturing systems are able to generate analysis of strategies concerning the activities within the remanufacturing process (e.g. collection activity/capacity, remanufacturing activity/capacity and disposal), most of them leave out any analysis of the returns process (e.g. the factors affecting the recovery process of used products). As a result, the returns quantity is seen as equal to the quantity of demands/sales or equal to simple percentages of the demands/sales. However, in relation to our objective to analyse the returns process through a modelling process, an interesting concept was introduced by Georgiadis, Vlachos and Tagaras (2006): the residence time. This concept can be used to tackle the issue regarding the uncertainty in timing of returns through the knowledge of the average time for which a product stays with the customer before it is returned.

2.8 Summary

The purpose of this chapter has been to examine and review the literature on research topics related to the reverse supply chain processes and SD simulation modelling. It was found that RL and CLSC can represent company strategies aimed at achieving environmental sustainability and economic benefits through reuse, remanufacturing and recycling activities. It is also important to highlight a differentiation between RL and CLSC based on a higher integration between the reverse and forward supply chain for the latter.

A discussion of the role of RL and CLSC regarding environmental issues and company strategies was provided. Despite the fact that such reverse supply chain processes already have a recognised role in gaining environmental benefits through, for example, the fulfilment of government regulations, the increasing interest among companies in employing RL and CLSC for operational processes optimisation was discussed. The role RL and CLSC can play in the achievement of economic benefits and efficiency in the usage of resources, as well as in improving life-cycle performance of the product, was introduced and explained. However, barriers were found regarding the development of reverse logistics and closed loops supply chain processes. Thus, the main issues and problems regarding the development of efficient reverse logistics and closed loop supply chain systems were also provided and discussed.

Although both theoretical information and an outline of the practical issues, elucidated through several examples of closed loop supply chains, have been provided to aid understanding of this research, one of the main focuses of this chapter has been on the modelling approaches applied to reverse logistics and closed loop supply chain processes. Specifically, an investigation of the existing literature on remanufacturing, reuse and recycling modelling, and closed loop supply chain modelling focusing on distribution, production planning and inventory control, has been provided. The objective was to build the knowledge in this area to address the research topic and to identify the best modelling approach for this research. For the same reason, an analysis of the main factors influencing a reverse supply chain process, in particular a closed loop supply chain process, has been presented.

Another research area covered during the review was system dynamics simulation modelling. Through the review of SD and its applications, its suitability and applicability for this research were highlighted. An introduction to SD and its modelling approach was briefly presented. Moreover, applications of SD simulation modelling to supply chain management and closed loop supply chain systems were examined in order to analyse the previous studies in which the topics and methodology used were similar to this research.

Chapter 3

METHODOLOGY

3.1 Introduction

This chapter provides a description of the methodology used in this research. In particular, we describe the system under study to clarify the purpose of the research and the approach used to conduct the research.

Before outlining the research approach, we introduce and describe the system which will be modelled and simulated in order to evaluate effective control strategies aimed at improving system performance. The assumptions adopted in relation to this system will also be presented in this section. We then discuss the modelling and simulation approach adopted, the use of the collected data from the case study companies, and the various stages designed for this research. As several of these stages involve the SD simulation modelling process, we also provide a detailed description of the steps involved in SD simulation modelling used in this research. The chapter also presents the background of the companies used as case studies for which face-to-face interviews with company management were conducted.

3.2 Description of the System under Study

The purpose of this research is to model the factors affecting a production and inventory system that combines returns and remanufacturing within the context of closed loop supply chains, and to evaluate effective control strategies aimed at improving the performance of the system. For this purpose, we will model and simulate a single product production and inventory system for remanufacturing within the context of close loop supply chains. The system involves several operations including: production, collection and inspection of used products, remanufacturing and disposal. Our focus in this study is on the return of products from customers/product users at the end of their useful life; other returns such as product recalls and B2B commercial returns are excluded in the study.

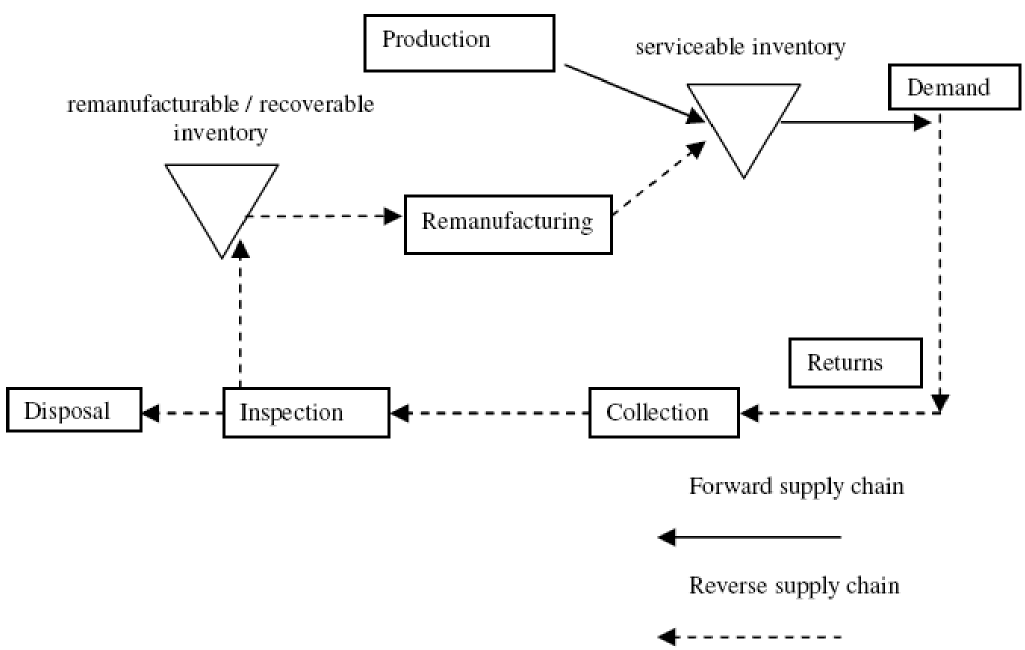


Figure 3.1: Production and inventory system for remanufacturing

The system under consideration is depicted in Figure 3.1. The forward supply chain involves the production of new products to meet customer demand. After product use, returns are collected, inspected and either stored as remanufacturable/recoverable inventory or disposed of depending on whether the quality of returns is suitable for remanufacturing according to the company's policy on quality standards. The serviceable inventory, used to fulfil external demands, is fed by the production of new or remanufactured products which are as good as new. Production and remanufacturing activity are important components of any production and inventory system for remanufacturing. Equally important to the process is analysis and decision making regarding inventory, operational and marketing activities.

A number of assumptions will be made throughout this analysis in order to simplify the system and facilitate the modelling process by helping focus on the most important factors:

- Uncontrollable disposal is not considered: instead of the product returning to the remanufacturer, it is disposed of in an uncontrolled manner, sometimes in opposition to the manufacturer's instructions or environmental regulations.
- The planned disposal of recoverable inventory is not considered.
- The capacity of several activities such as collection, inspection, remanufacturing and production are considered infinite.
- Backordering and lead times are not considered.

3.3 Research Approach

The approach adopted in this research is presented in this section. The modelling and simulation approach used to investigate the system under study is first discussed. This is followed by an outline of the information and data collected from the case study companies. Finally, the various stages involved in conducting the research are described.

3.3.1 Modelling and Simulation Approach

The complexity of modelling the production and inventory system for remanufacturing suggests the need to focus on two processes of primary interest in our research: the returns process and the remanufacturing process. For this reason, we will use a divide-and-conquer approach by modelling the system by considering the returns process and the remanufacturing process as two separate sub-processes which are created, tested and simulated independently of each other. However, the two models are more complementary than opposed, because for both the entire system is modelled in which assumptions are relaxed in order to focus the analysis on the two processes. A more detailed description of how this approach will be used is presented in Section 3.3.3.

In terms of the modelling and simulation method, in this research we use system dynamics (SD) (Forrester 1958, 1961), a methodology used for studying and managing complex feedback systems, particularly business and social systems. An SD approach as a modelling and simulation method for dynamic industrial management processes is an excellent tool for those management systems in which new decisions have to be made and new circumstances appear with the passing of time (Coyle 1996).

The selection of an SD approach for this research was based on its ability to model systems with complex feedback structures using visual representation which can then be converted into mathematical formulas by software. The complex feedback structures are obtained by iterations of the physical and informational flows and managerial policies defined by the system variables. The SD model can then be simulated in order to reproduce the dynamic behaviour of the system, which in turn enables an evaluation of the system improvement strategies. SD differs from other approaches such as analytic approaches. The former involves identifying influence relationships among the variables of a complex system in order to undertake a comparison between the reality and the dynamic behaviour of the model which represents the system in its totality. Moreover, as previously mentioned in Section 2.7, SD is suitable for modelling and simulating systems that contain multiple nonlinear relationships and dynamic forces that render not feasible the use of an analytical approach to solving model equations (Angerhofer & Angelides 2000; Coyle 1996). For these reasons, we believe that such an approach is suitable for our research. Specifically, through a simulation approach it enables the modelling of factors, operations processes and company policies to consider in a production and inventory system for remanufacturing, as well as the evaluation of effective control strategies aimed at improving the performance of the system.

3.3.2 Data Collection

Case studies will be used in this thesis to gain support for the research findings as well as to further validate the developed models for production and inventory systems for remanufacturing. In particular, through the case studies we will be able to assess the research findings obtained from the simulation analysis of the models. Moreover, some of the information and data collected from the companies will be useful in selecting the variables and the relationships among them to be used in the model development. For these reasons, we collected as much data and information as possible through interviews with company management representatives of three companies involved in reverse logistics/closed loop supply chain and remanufacturing activities. These companies are: the Australian Mobile Telecommunications Association (AMTA), Fuji Xerox Australia and CEVA Logistics. However, specific data (e.g. on costs for particular company activities) which would be useful for our research were not possible to collect due both to company privacy policies and the difficulty for companies in recording such data.

The selection of these particular companies was based on their involvement in remanufacturing and returns processes. In particular, the data and information collected from the first two companies will be used for the analysis that focuses on the returns process, while the data and information collected from CEVA Logistics will be employed for the analysis that focuses on the remanufacturing process. These choices on the use of specific company data for the analyses of the two processes was due to the nature of the data and information collected, as well as to the different characteristics of the reverse logistics/closed loop supply chain activities in which the companies are involved. Specifically, AMTA, in contrast to the other two companies, is not involved in closed loop supply chain activities or in remanufacturing. The reverse logistics activity of this company relates to a recycling project for mobile phones. However, within this project, several incentives for the returns process have been developed in order to increase returns/collection rates and customer engagement in the returns process. Moreover, quantitative data were collected regarding the effects of such incentives on customer behaviour and the returns rate. Both Fuji Xerox Australia and CEVA Logistics are involved in remanufacturing activities. However, the former has also focused on the development of activities/incentives for the returns process, such as changes in product design and service agreements with customers, which made it useful for our examination of the returns process. In contrast, CEVA Logistics works more as a logistics service provider for reverse supply chains, and has a more passive attitude towards the returns process compared to Fuji Xerox Australia. However, qualitative and quantitative data were collected from CEVA Logistics regarding its activities in the remanufacturing process. For Fuji Xerox Australia, it was possible to mainly collect qualitative data on its returns process.

Some background on the two companies with which face-to-face interviews with company management were conducted (Fuji Xerox Australia and CEVA Logistics) is presented in Section 3.5.

3.3.3 Research Stages

This research will entail two main stages and several sub-stages, as depicted in Figure 3.2. The two main stages concern the development of generic SD models of a production and inventory system of remanufacturing using the theoretical basis drawn from the literature review as well as from some of the data and information collected from the case study companies. Specifically, in the first main stage we model the system considering all the assumptions presented in section 3.2. The model developed can then be simulated through the design and analysis of different scenarios, focusing mainly on the returns process. Such an analysis allows examination of the changes in system behaviour in response to the different inputs that the decision makers and other factors involved can generate, and in turn allows us to formulate strategies which can improve system performance. In the second main stage we will relax some of the assumptions related to the remanufacturing process in order to remodel the system and simulate the new model focusing on scenarios analysis. The relaxed assumptions relate to remanufacturing and production capacity/lead times and backordering activity.

The several sub-stages involve the process steps of SD simulation modelling and the use of the case study data. A detailed description of the steps involved in the SD simulation modelling is provided in Section 3.4. For the first main stage, once the qualitative and quantitative model of the system has been created, and the variables and their relationships affect on the returns process are defined, modelled and formulated, a validation analysis can then be performed. Next, a simulation analysis will be applied in order to investigate and evaluate system improvement strategies using a particular measure of performance. The simulation will employ scenarios analysis focusing on the main variables involved in the returns process of the system. As the developed model is a generic model, in order to assess the robustness of the findings obtained through the simulation analysis, the case studies will then be applied. Specifically, the data and information obtained from AMTA and Fuji Xerox Australia will be used in the analysis of the returns process.

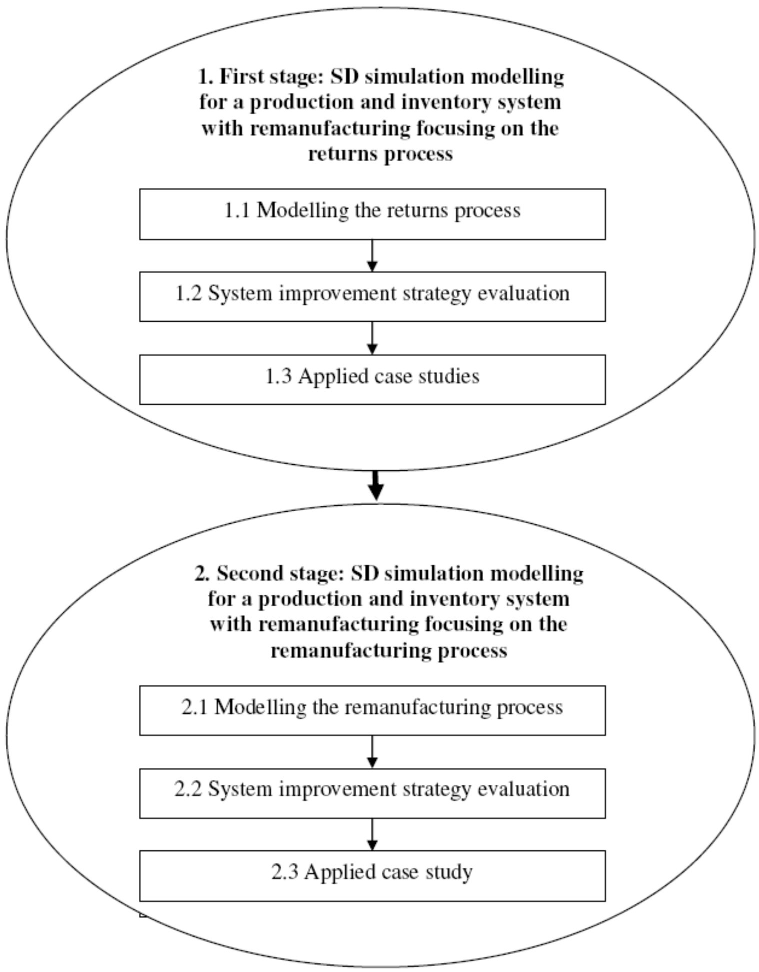


Figure 3.2: Research framework

Similar sub-stages will be involved in the second main stage concerning the modelling and simulation analysis of the remanufacturing process. However, in this case the analysis will focus on the main variables and their interrelationships that affect the remanufacturing process. Moreover, the data and information obtained from CEVA Logistics will be employed as a case study to test the robustness of the model and assess the research findings concerning the remanufacturing process.

The modelling and simulation analysis of the returns process will be described in Chapter 4, and the modelling and simulation analysis of the remanufacturing process in Chapter 5.

3.4 Steps of System Dynamics Modelling

A detailed description of the steps involved in the SD simulation modelling used in this research is provided in this section, including a description of the techniques and tools involved in the qualitative and quantitative modelling. The approach utilised for the models validation and simulation are then discussed.

3.4.1 Qualitative Modelling

The first step in the modelling process is represented by a description of the system structure through a Causal Loop Diagram (CLD). A CLD assists in the understanding of system structure as it identifies the important factors and variables that influence a system as well as the causal influences among these variables. Moreover, a CLD or influence diagram is an essential tool not only to describe the model but also to understand the influences at work in the system and the causes of its dynamic behaviour (Coyle 1996). A CLD consists of variables connected by arrows denoting the hypotheses and the mental models of the modeller in order to represent the feedback structure of systems in which the causes for problems can be found (Sterman 2000). Positive as well as negative feedback interrelationships can be represented through feedback or causal loops.

A simplified example of a CLD for a traditional production and inventory control system is presented in Figure 3.3. Solid arrows represent the physical or consequence flows. Identifying the physical flow should be the first step in drawing a CLD since it provides understanding and identification of the process (Coyle 1996). The broken arrows represent information or action flows. Specifically in Figure 3.3, ‘production’ through produced items physically feeds the ‘actual serviceable inventory’ which in turn is depleted by the ‘sales’. The actual serviceable inventory influences through information flows both production and sales. The latter influences the desired serviceable inventory which in turn influences production. The influence between variables is indicated by the ‘+’ and ‘–’ signs, which show how the dependent variable changes when the independent variable changes (Sterman 2000).

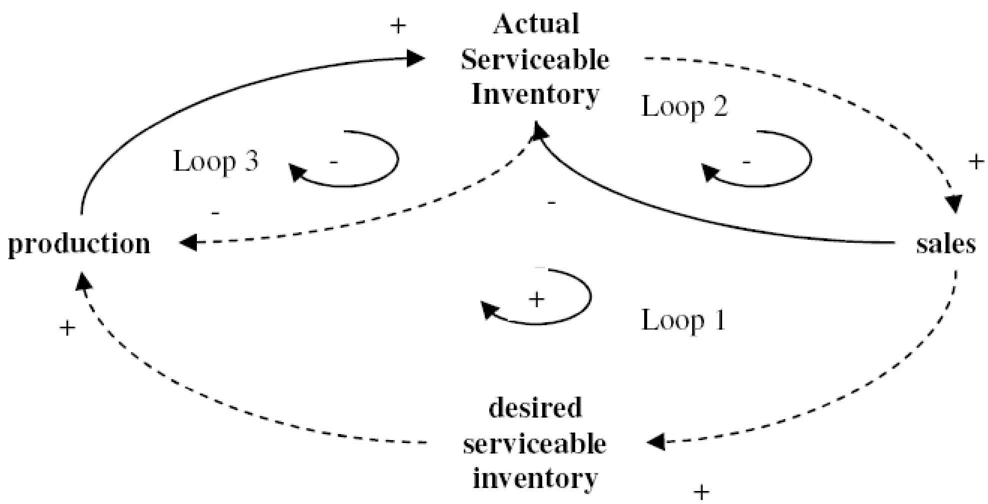


Figure 3.3: Example of CLD (adapted from Georgiadis & Vlachos(2004a))

For example, regarding the information flows, a decrease/increase of actual serviceable inventory requires an increase/decrease of production rate (negative influence) as well as leads to a decrease/increase in sales (positive influence). A decrease/increase in sales leads to a decrease/increase in the desired serviceable inventory which in turn decreases/increases the production rate. The same effects are valid for the physical flows. For example, between production and actual serviceable inventory, an increase/decrease in production rate leads to an increase/decrease in inventory. These positive or negative influence relationships among the variables also determine the system policies under study. For example, in Figure 3.3 a control policy for the actual serviceable inventory is considered through the negative and the positive influences on production and sales, respectively. Specifically, the actual available serviceable inventory controls both the production quantity (i.e. to produce only what is required) and the quantity of sales (i.e. the quantity of sales depends on the available serviceable inventory).

One of the main objectives of the system dynamics modelling process is to discover and represent the feedback processes represented by feedback loops which determine the dynamic behaviour of the system (Sterman 2000). The dynamic behaviour of the system results from the interaction of two types of feedback loops (Coyle 1996; Sterman 2000): goal-seeking or negative loops, and growth-producing or positive loops. A positive loop generates a continuous growth and tends to reinforce or amplify the value of the system variables involved. Conversely, to counteract this continuous amplification, negative loops inject equilibrium into the system by seeking the right goal for the value of the system variables. For example, the behaviour of the system as presented in Figure 3.3 is defined by one positive feedback loop (Loop 1) and two negative feedback loops (Loop 2 and Loop 3). Specifically, the positive feedback loop generates an exponential growth in the system through a continuous amplification in the value of the variables involved (production, actual serviceable inventory, sales and desired serviceable inventory). For example, an increase in production causes an increase in actual serviceable inventory which in turn increases sales. Then sales in turn increases desired serviceable inventory, which in turn again increases production. However, the two negative loops avoid this continuous amplification through the negative relationships between actual serviceable inventory and production (Loop 3), and between sales and actual serviceable inventory (Loop 2). An increase in production increases actual serviceable inventory, which in turn decreases production. Similarly, an increase in actual serviceable inventory increases sales, which in turn decreases actual serviceable inventory. In order to find the sign of a feedback loop, a simple method is to count the number of negative links in the loop. If this number is even, the loop is positive; otherwise is negative (Sterman 2000).

3.4.2 Quantitative Modelling

The next step after the development of the CLD is the quantitative analysis of the model. In order to study the quantitative aspects of the model, the variables used to develop the CLD are now defined and classified as: (1) level or stock variables; (2) rate or flow variables; and (3) auxiliary variables (Coyle 1996; Sterman 2000). The stock variables determine the state of the system by accumulating the difference between the inflow to a process and its outflow (Sterman 2000), while the flow variables determine the physical flows in the system and generate change in the stocks, which is then used to make decisions. The auxiliary variables can be useful to clarify the structure and process of the model. They usually represent constants or exogenous inputs into the model as well as converters or intermediate variables for the mathematical equations of the model (Kirkwood 1998; Sterman 2000).

A different diagram is used to represent the process of quantitative analysis of the model, which is called the Stock and Flow Diagram (SFD). Through the SFD, it is possible to analyse the dynamic relationships among stock, flow and auxiliary variables. These relationships are used to establish mathematical equations in turn to run simulations of the model. Indeed, while the CLD represents a real system of variables connected by signed links, a quantitative model represents the same system using variables in equations (Coyle 1996).

The SFD for the production and inventory control system the CLD of which was presented in Figure 3.3 is shown in Figure 3.4. In this case, the physical flow is represented by the double line of arrows. The stock variable actual serviceable inventory, represented by a rectangle, defines the level or accumulation of serviceable inventory. The latter is fed by the flow variable production and depleted by the flow variable sales. The flow variables, represented by valves, dynamically change the level of the stock variable. ‘Desired serviceable inventory’ is the auxiliary variable and is used in the structural process of the model. The single lines with arrows represent the relationship of influence and flow of information among the variables. Moreover, they are used to establish the mathematical equations for the model.

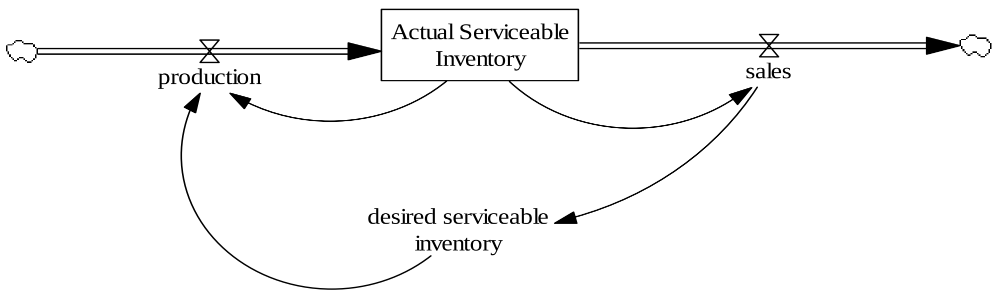


Figure 3.4: Example of an SFD

The mathematical meaning of an SFD results from the conventions used by Forrester (1961) to define this particular diagram based on the hydraulic metaphor of the flow of water into and out of reservoirs (Sterman 2000). Specifically, stocks (reservoirs) accumulate material (water) which changes dynamically due to the flow variables (inflow and outflow of water). For this reason, stocks can be represented mathematically through the differential equation (Sterman 2000):

$$d\,(Stock) \,/\, dt = Inflow(t) - Outflow(t) \tag{6}$$

or the equivalent integral equation:

$$Stock(t) = \int_{t_0}^{t} \left[Inflow\,(t) - Outflow(t) \right] dt + Stock(t_0) \tag{7}$$

For example, the actual serviceable inventory in Figure 3.4 can be represented as (Georgiadis & Vlachos 2004a):

$$\begin{aligned} &Actual\ Serviceable\ Inventory(t) = \int_{0}^{t} \left[production(t) - sales(t) \right] dt + \\ &+ Actual\ Serviceable\ Inventory(0) \end{aligned} \tag{8}$$

The mathematical formulation of the flow and auxiliary variables of the system results from the structure and influence relationships within the system. These variables can either be represented by constants and exogenous inputs or be a function of their variables of influence (Sterman 2000). For example, the variable production in Figure 3.4 can be represented as a function of the desired serviceable inventory and actual serviceable inventory:

$$production(t) = f\,(\,desired\ serviceable\ inventory, Actual\ Serviceable\ Inventory\,) \quad (9)$$

3.4.3 Model Validation

Before commencing simulation of the model, validation and verification processes must be performed. The validity for an SD model defines its capacity to reflect the structure and behaviour of a real process model, although a perfect representation of reality through modelling is almost impossible. The responsibility of modellers in using the best model available for a specific purpose must include an awareness of the impossibility, during the verification and validation of models, of achieving an accurate representation of reality with conclusions that are entirely correct (Sterman 2000). However, according to Sterman validation tests of a model have to be performed in order to discover the flaws in the model and set the stage for improved understanding. Specifically, the calibration of the model (i.e. the comparison between the actual behaviour of the real system or historical behaviour and the simulated behaviour of the model) as well as model testing concerning the structure and behaviour of the model can be used for this purpose. Still Sterman (2000), regarding model testing, states that:

> *… testing involves far more than the replication of historical behaviour. Every variable must correspond to a meaningful concept in the real world. Every equation must be checked for dimensional consistency. The sensitivity of model behaviour and policy recommendations must be assessed in light of the uncertainty in assumptions, both parametric and structural.*

In our study the models calibration will not be performed because of a lack of suitable data which were not possible to collect from the case study companies due both to company privacy policies and to the difficulty for companies of recording these data. However, other models testing concerning the validation process will be performed in order to consider the models most suitable for evaluating and investigating strategies aimed at improving system performance through a simulation analysis. Moreover, the data and information that was collected from the companies will be used to further validate the models. Indeed, regarding the structure of the models we will try as far as possible to select particular variables, the relationships among them and their value which correspond to meaningful concepts in the real world (Sterman 2000) as well as to some of the data and information collected. Moreover, these data and information will be used to support and assess the simulation results.

In terms of the models testing for the validation process, we will follow the accurate study and analysis of model validity and validation in SD proposed by Barlas (1989, 1996). A formal and logical process for model validation is shown in his study. According to the author, the structural and behavioural validity of a model should be established through tests, which are grouped as ‘direct structure tests’, ‘structure oriented behaviour tests’ and ‘behaviour pattern prediction tests’. Direct structure tests, for which simulation is not required, compare each mathematical equation of the model with the available knowledge from a real system. These tests utilise several comparisons and include the form of the equations; the conceptual or numerical value of model parameters; the value of the output variable applying extreme conditions values to the input variables of the equations; and dimensional consistency for both sides of each equation. On the other hand, structure oriented behaviour tests or indirect structure tests involve simulation of the entire model and apply structure model validation through a quantitative comparison with the real system. Several comparison tests can be applied such as extreme condition and behaviour sensitivity tests: the first test compares the model and the real system behaviour under the same extreme values for selected parameters; while the second test compares the high sensitivity of particular parameters between a model and the real system. The behaviour validation of the model can also involve behaviour pattern prediction tests (Barlas 1989). According to the author, these tests determine whether the behaviour patterns generated by the model reflect the major patterns exhibited by the real system. Specifically, they involve comparison between the model-generated behaviour and an observed behaviour.

3.4.4 Simulation of Scenarios and Evaluation

In order to investigate and evaluate system improvement strategies regarding the company policy considered in the model structure, simulations based on scenario analysis given particular parameters are developed. In system policy evaluation, the activities of scenario specification and ‘what if’ analysis define respectively the environmental conditions that might arise in the system and the effects of the policies considered (Sterman 2000). For this reason, in this research we will use scenarios analysis as a combination of the two previous activities in order to define the various conditions of the system obtained by changing scenarios for the system policies under study.

The choice of how to create these scenarios derives from the purpose in using them in the simulation modelling. Indeed, one of the purposes of using scenarios in simulation modelling is to assess how well alternate policies would perform under the conditions depicted (Becker 1983; Maani & Cavana 2000). Then, in the simulation analysis of the modelled returns process and remanufacturing process we will assess alternative system policies through scenarios obtained by changing the value of the parameters involved in these particular policies.

3.5 Company Backgrounds

In this section we outline the actual practices undertaken with respect to returns management, inventory control and remanufacturing by the two companies with which face-to-face interviews were conducted: Fuji Xerox Australia and CEVA Logistics. In the case of AMTA, the employed data were mainly drawn from secondary data in the existing literature (company annual reports), which were suggested by the company management during telephone interviews. For this reason, an outline of this company's background and reverse logistics activities will be presented in Chapter 4.

3.5.1 Fuji Xerox Australia

Fuji Xerox is a leading global corporation which has achieved success through a re-investment of its business into remanufacturing the components of its office equipment products (Benn & Dunphy 2004). In Australia, Fuji Xerox supplies and services digital printing equipment such as printers, fax machines and photocopiers. Fuji Xerox has a reputation for market-leading research and development and provides quality colour and black and white printers for organisations of all sizes (Environment Protection Authority 2002; Fuji Xerox Australia Pty Limited 2007c). Product remanufacturing is an integral part of the business for this company. The Fuji Xerox Eco Manufacturing Centre in Zetland, Sydney collects, disassembles and remanufactures used products for reuse through a process that uses less raw materials and energy, thereby reducing waste and disposal costs. The Centre remanufactures used parts and components, which are given the same guarantee as new products, for the Asia-Pacific region. Moreover, 80% of spare parts requirements for Fuji Xerox Australia are provided by the Eco Manufacturing Centre, parts that would have otherwise gone to landfill (Fuji Xerox Australia Pty Limited 2007a). In 2006, 220,000 parts were remanufactured, saving Fuji Xerox in the order of AU$13 million in new part costs and creating revenue of AU$5.4 million in exports (Fuji Xerox Australia Pty Limited 2007b). Through its 60 remanufacturing programs developed each year, Fuji Xerox is continually expanding, and remanufacturing is now a core business function for the company (Benn & Dunphy 2004).

The reverse logistics process of this company aims at zero waste discharge. For example, used toner cartridges and other parts or consumables (such as magnetic rollers and circuit boards) are collected and remanufactured; metals are collected by scrap metal merchants and recycled; cardboard and paper are sent to paper recyclers; and pallets are reused by suppliers (Environment Protection Authority 2002). Several environmental and economic benefits are obtained through these activities:

- The cost saving has a strong impact on operating expenses and remanufactured products are superior to the original parts.
- The information flow between the remanufacturing and production processes facilitates better product design for parts to be more readily remanufactured.
- Better product performance and competitive pricing.
- Increased profitability, design expertise and labour skills, reduced imports and value-added exports.
- Reduced waste to landfill and less pollution, leading to environmental benefits.

The total investment in this remanufacturing activity was paid off within two years through the savings on product purchases, which are presented in Table 3.1.

Table 3.1: Fuji Xerox Australia savings on product purchasing (adapted from Environment Protection Authority (2002))

1996	**AU$8 million**
2001	**AU$24 million**
Forecast increase in savings	**20% per year**

Another advantage of remanufacturing activity is the constant evaluation and testing of machines and components. This leads to continual product improvements and the extension of product life, which provides the opportunity to remanufacture components several times over (Fuji Xerox 2007). Sub-assemblies and components are evaluated to identify reasons for failure or to determine the remaining life of the part, through diagnostic tools which compare the signature of a used part to that of a new part. Consequently, the latest generation of digital printers and copiers are built in modular format such that all modules can be remanufactured. In this way, remanufacturing activity can focus on modules with easier remanufacturability rather than on the whole machines. This process leads to faster recovery of returns from customers and reduces uncertainty over quality and cycle processing time of returned products, with a subsequent reduction of operating expenses.

Product design that is suitable for disassembly and remanufacturing, achieved through an exchange of information between remanufacturing and production processes, could lead to further benefits. In line with the preponement concept of avoiding unnecessary processing expenses, Fuji Xerox has advanced reverse logistics activities on the reverse supply chain. All moving components in the machines are contained in seven discrete modules. These modules can be easily removed and replaced by customers ready for collection and remanufacturing (Fuji Xerox 2007). Moreover, customer-driven returns and training in assembly/disassembly of the modules are services offered to customers. These activities can lead to a more productive and cost-effective system, through the guaranteed faster return of products/components, which leads to more simplified remanufacture planning, scheduling and controlling. If returns are sorted and graded before entering the remanufacturing process, several significant operational benefits are achieved in terms of quality variability of returns, processing time, size of the facility reserved for returns and amount of recoverable inventory (Guide & Wassenhove 2001).

The provision of service agreements to customers is a company strategy employed by Fuji Xerox Australia aimed at reducing uncertainty over the quantity of returns in production and inventory planning/scheduling. In Australia this company is mainly a service provider, supporting this service with its own leasing finance company (Benn & Dunphy 2004). Following this, the objective of Eco Manufacturing Plant is to produce high-quality machines and to recover used components for remanufacturing. For this reason, most machines are leased to customers. This allows Fuji Xerox to keep track of the quantity and location of equipment and to maintain control over the remanufacturing process and returns rate (Fuji Xerox 2007). A key innovative technology system, System 21, supports this activity. This system tracks all consumables and recoverable spare parts and has allowed an increase in the recovery rate from 80% to 98% (Benn & Dunphy 2004).

3.5.2 CEVA Logistics

CEVA Logistics Australia is one of the top five companies in the logistics industry in Australia (CEVA Logistics 2008). It provides a range of logistics services for a number of customers and, in particular, provides the materials handling services and materials management services for the reverse supply chain of several Telstra products. Telstra is a communications company in Australia that provides customers with integrated telecommunications and information services (Telstra Corporation Limited 2009). In this context, the reverse supply chain focuses primarily on three kinds of products: (1) electronic components such as modems, telecommunications equipment and computer components; (2) emergency temporary phones; (3) mobile phones; and (4) home phones. The process entailed is different for each kind of product:

- (1) Returned products from Telstra warehouses are collected by CEVA Logistics which sorts them in order to dispose of the non-remanufacturable items and send the remanufacturable returns to the remanufacturing centres (generally the original producers). Once the returns are remanufactured, the as-good-as-new products are sent back to CEVA Logistics to be redistributed.

- (2) Customers or the Telstra technicians arrange an appointment in order to collect the returns (damaged emergency temporary phones). Telstra then generates a recovery order for CEVA Logistics. The latter recovers the returns and begins an inspection, testing and cleaning process. From there, the returns are either disposed of or sent to the remanufacturing centres. The remanufactured products are then sent back to CEVA Logistics to be redistributed.
- (3) CEVA Logistics collects the returned mobiles from Telstra shops and inspects them in order to send the remanufacturable returns to the Telstra remanufacturing centre in New South Wales. Utilising a backhauling approach, the company collects from the Centre the remanufactured products for redistribution to shops.
- (4) Returns are collected from Telstra shops and are all disposed of, as their value does not justify the cost of the remanufacturing process.

3.6 Summary

This chapter has outlined the methodology adopted to conduct this research. We described the system on which the research will focus, the approach by which the research will be conducted, the process steps of the SD simulation modelling to be undertaken over the various stages of the research, and the case study companies employed.

In line with the goals of this research, the system under study represents a production and inventory system for remanufacturing for which all of the processes have been briefly explained and the assumptions made presented. The aim of this brief outline was to introduce the system and its activities which will be modelled and explained in detail by focusing on the returns and remanufacturing processes in Chapters 4 and 5, respectively.

The chapter described the approach and method used in modelling and simulating the production and inventory system for remanufacturing. The use of the information and data collected from the case study companies was briefly discussed, and the design of the various stages of the research was outlined. In particular, the research includes two main stages which involve several sub-stages that correlate to the process steps of SD simulation modelling of the production and inventory system for remanufacturing, which focus first on the returns process and then on the remanufacturing process. Moreover, the assessment of the research findings obtained from the simulation analysis of the models will then be supported by the information drawn from the case studies.

The process of SD simulation modelling was presented as following four main steps: qualitative modelling; quantitative modelling; model validation and simulation; and scenarios analysis. In particular, for the first two steps an application for a traditional production and inventory control system was developed in order to clarify the activities involved.

The case study companies—the Australian Mobile Telecommunications Association, Fuji Xerox Australia and CEVA Logistics—were introduced, whose activities in relation to returns management, inventory control and remanufacturing made them useful for our research. The company background and information regarding previous activities were only discussed for Fuji Xerox and CEVA Logistics; since only secondary data was obtained for AMTA, this company will be discussed in Chapter 4.

Chapter 4

MODELLING THE RETURNS PROCESS

4.1 Introduction

The aim in this chapter is to develop a generic SD simulation model of the production and inventory system for remanufacturing, focusing on the returns process. Specifically, the return process will be modelled using several factors which influence relationships within the process. The factors considered are the residence time of the product with the customer, the service agreement with the customer and customer behaviour in returning used products.

This chapter briefly describes the returns process and the assumptions made about the system during the modelling stage in order to focus on the most important factors. As the modelling stage involves the process of SD simulation modelling, we explain in detail the steps used to create the SD model of the system. Specifically, a qualitative model or a Causal Loop Diagram (CLD) of the system is created by identifying the main factors or variables that affect the behaviour of the system as well as the relationships among these factors. As part of this qualitative modelling process, the main feedback loops are identified. A quantitative model or a Stock and Flow Diagram (SFD) is obtained from the

CLD to identify and classify the stock, flow and auxiliary variables, and the relationships among them, in order to establish mathematical equations representing the dynamic behaviour of the system. The quantitative model can be used to simulate scenarios, focusing particularly on the returns process, in order to evaluate and investigate business strategies aimed at improving the performance of the system. However, before any confidence can be obtained about the accuracy of the model, it must first be validated. Thus, we discuss the methods used for validation of the model created. The simulation findings are assessed and the developed model further validated with reference to the real world experiences of two companies (the Australian Mobile Telecommunications Association [AMTA] and Fuji Xerox Australia) directly involved in reverse logistics and remanufacturing activity.

4.2 Model Building

The modelling process in SD is characterised by a sequence of iterative activities and stages that involve continuous revisions and changes. Indeed, the modelling process can be defined as a continual process of iteration among the problem articulation, the generation of hypotheses, data collection, model formulation, testing and analysis (Sterman 2000). In this section, the final results of this process of iteration, which leads to the model building for the first production and inventory system for remanufacturing, are presented.

First we briefly introduce the returns process, the main assumptions made about the system, and the major factors considered that affect the process. Then, a detailed explanation of both the development of the qualitative model or CLD and the quantitative model or SFD of the system is provided.

4.2.1 Returns Process and Assumptions

All of the assumptions considered in relation to the production and inventory system for remanufacturing, as presented in Chapter 3, will be used in order to model and develop a simulation analysis of the system, focusing particularly on the returns process. The assumptions are summarised as follows: uncontrollable disposal is assumed; the planned disposal of recoverable inventory is assumed; backordering and lead times are not considered; and the capacity of collection, inspection, remanufacturing and production activities is considered to be infinite. Figure 4.1 shows the area of the system under study which characterises the return process of used products. Specifically, the products sold to the customers (*demand*) after a period of time become used products, which in turn become company returns. The latter are collected, inspected and stored as recoverable inventory to be remanufactured.

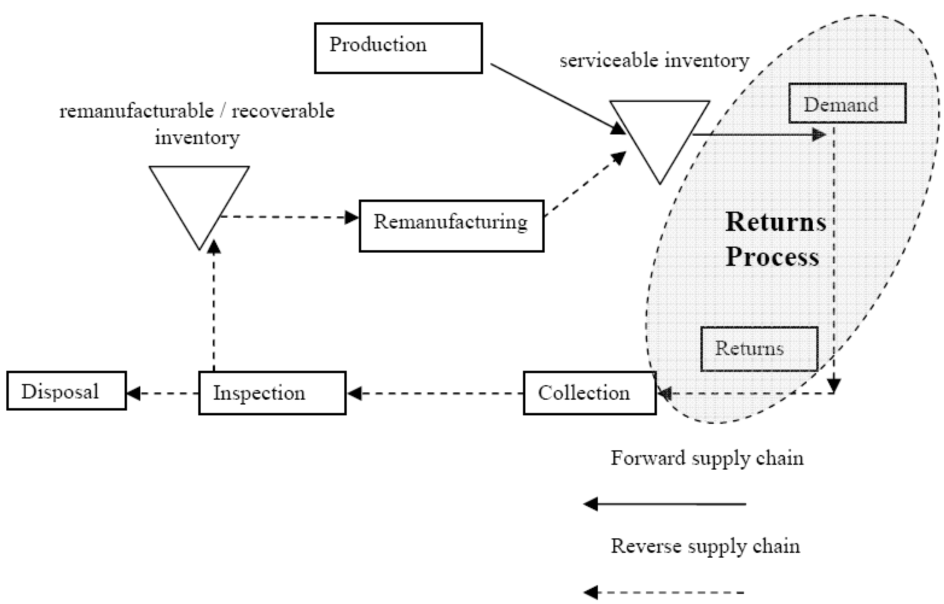


Figure 4.1: The returns process

In the model representing the system, the returns rate incorporates uncertainty in quantity and timing of returns and a pull inventory control policy is applied. This policy is obtained through reorder point inventory replenishment policies, which are basic features of several industries in the context of supply chain/inventory planning. The returns rate, which is used to calculate the number of returns after the time of use, is represented as the ratio between the probable returns flow of sold products and the demand. The probable returns flow and the time of use are calculated on the basis of the relationship between two factors: the *return index* and the *residence time*. The latter is the factor defined in the study of Georgiadis, Vlachos and Tagaras (2006).

The ways in which companies manage the returns process of products sold to customers, through service agreements and sales contracts with retailers or the customers themselves, can influence the returns rate and particularly the quantity of returns. For example, leasing contracts make sure that almost all products are returned after the residence time. In the model, the *service agreement with customer* factor is used to relate the quantity of returns with the demand for different products in different industries. Moreover, *customer behaviour* is another factor which can influence this relationship. The attitude of the customer in terms of their return activity and their response to a company's returns process incentives can affect the returns rate and in particular the likelihood of a particular product being returned. Hence, the *return index* is obtained by considering the relationship between company incentives/service agreements developed in order to recover used products and actual customer behaviour in returning products. Put simply, it is the tendency of the product to be returned by the customer during its lifetime, which varies for different products and industries. This is explained in more detail later in the chapter.

4.2.2 Qualitative Modelling

A CLD is a visual tool representing the feedback structure of systems as such diagrams show cause and effect relationships and feedback processes (Morecroft 2007) that are responsible for the dynamic behaviour of the system. For this reason, in this section the

CLD of the production and inventory system for remanufacturing is presented in order to understand the causal influences among the system variables as well as the feedback structure of the system. The first stage in developing the CLD involves the identification and description of the variables used for the modelling of the system. The list of all of the variables used for this model, including the type and unit characteristic of each, is presented in Table A.1 of Appendix A. Following the identification of the system variables, the causal influences among them are identified either by positive '+' (i.e. if the cause increases/decreases then the effect increases/decreases) or negative '–' (i.e. if the cause increases/decreases then the effect decreases/increases) arrows. In particular, solid arrows represent the physical flows within the system, while broken arrows represent information or action flows. The main objective in identifying the causal influences among the system variables is to define and represent the feedback structure of the system through feedback loops. The latter determine the dynamic behaviour of the system. In particular, positive feedback loops generate exponential growth behaviour, while negative feedback loops generate goal-seeking behaviour.

The CLD representing the production and inventory system for remanufacturing is presented in Figure 4.2. The behaviour of the system is represented by seven negative feedback loops labelled as B1, B2, B3, B4, B5, B6 and B7. However, these feedback loops are not represented in Figure 4.2 because of the limited space in the diagram. They will be shown in a clearer way later. These loops balance the system and push typical production and remanufacturing factors towards stable levels rather than causing them to grow exponentially. Negative feedback loops operate to control the output of activities in order to direct the state of the system towards achieving a target value (Sterman 2000). Therefore, if the process generates outputs that are far from the target level, a negative feedback generates corrective actions to return the process toward the desired value.

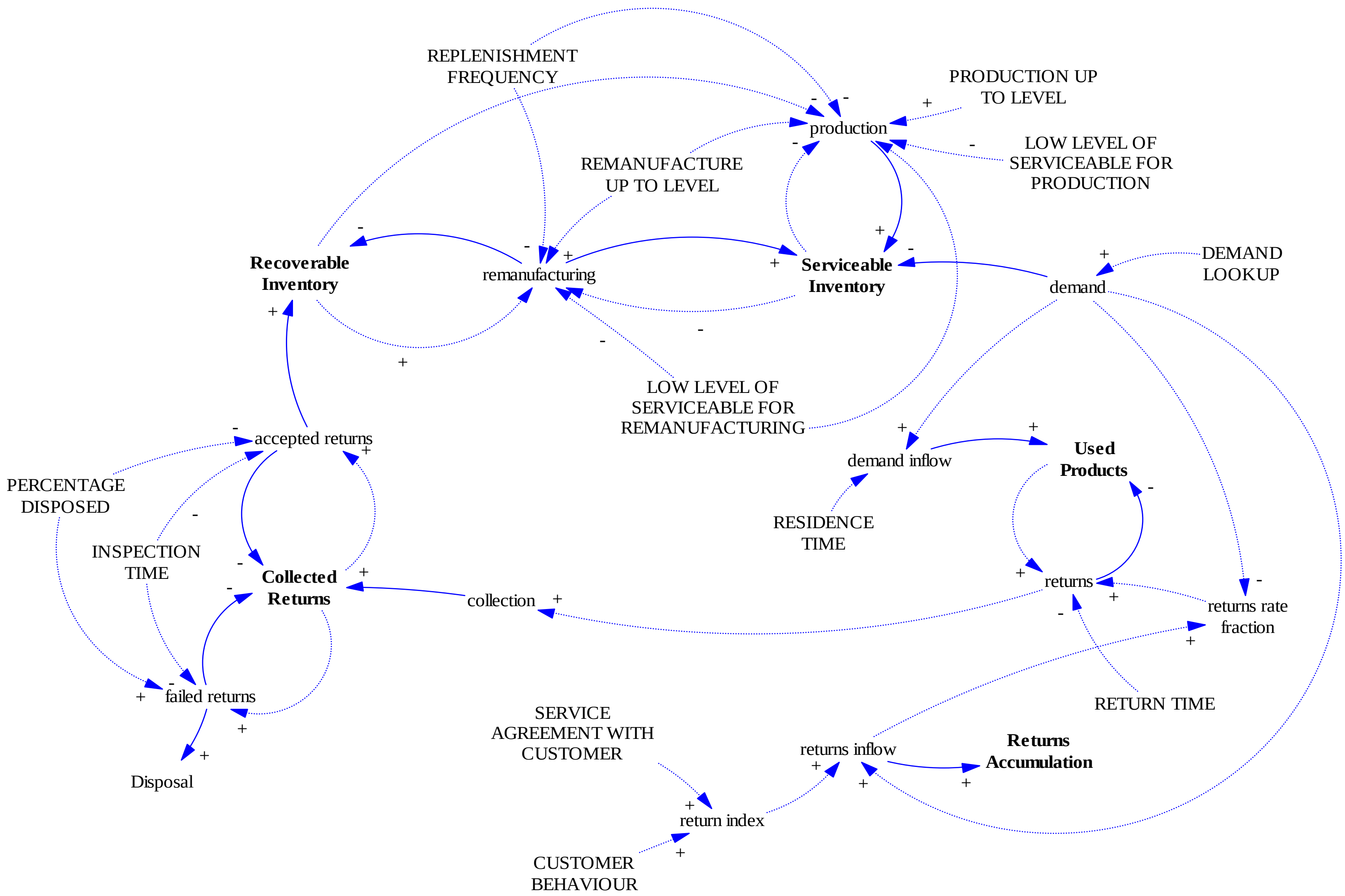


Figure 4.2: Causal Loop Diagram

The behaviour of the collection activity in the production and inventory system for remanufacturing is represented by two negative feedback loops, B1 and B2. These are shown in Figure 4.3 and Figure 4.4, respectively. An increase in *returns* increases the rate of *collection* which in turn increases the level of *Collected Returns*. At this stage of the process, returned products are inspected in order to check their quality and remanufacturability. Figure 4.3 shows the inspection process in the case of a failure at the quality test.

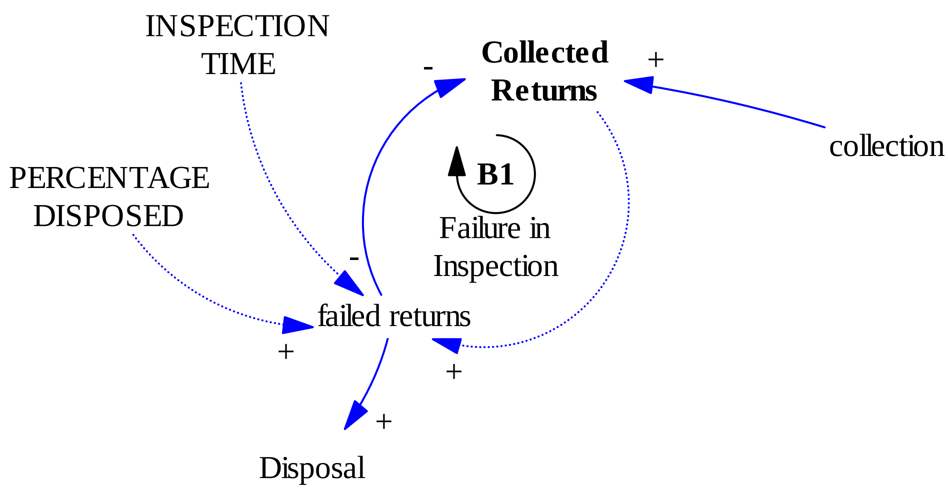


Figure 4.3: Failure in inspection feedback loop

Failed items decrease the level of *Collected Returns*, through a *failed returns* flow, and at the same time increase the level of *Disposal* which represents the quantity of non-reusable items that are disposed of. The flow rate of failed items depends on the value of *PERCENTAGE DISPOSED* and *INSPECTION TIME*. The former affects the flow rate positively as any change in the percentage leads to a similar change in the quantity of failures. For example, an increase in the percentage value of disposal leads to an increase in the flow of failed items for a given time period. *PERCENTAGE DISPOSED* also represents the quality standards policy of the company and is affected by several parameters and techniques used to check the returned items. It is defined as an average percentage of collected returns disposed of and differs for different products and different quality standard policies used (Vlachos, Georgiadis & Iakovou 2007). *INSPECTION TIME* represents the period of time required to inspect collected items. This negatively affects the inspection flow as a faster/slower inspection leads to an increase/decrease in the flow. Since an increase in *Collected Returns* causes an increase in *failed returns*, which in turn causes a decrease in *Collected Returns*, a negative feedback loop (B1) is created.

The inspection process, in the case of acceptance at the quality test stage for remanufacturable items, is represented in Figure 4.4. Accepted items increase the level of *Recoverable Inventory* that are ready to be remanufactured through the *accepted returns* flow. The flow rate of accepted items depends inversely on the value of *PERCENTAGE DISPOSED*, as a lower percentage of disposed items leads to a higher level of remanufacturable items. Thus, an increase in *accepted returns* rate causes a decrease in the *Collected Returns* level, which in turn causes a decrease in the *accepted returns* rate, hence forming the negative feedback loop B2.

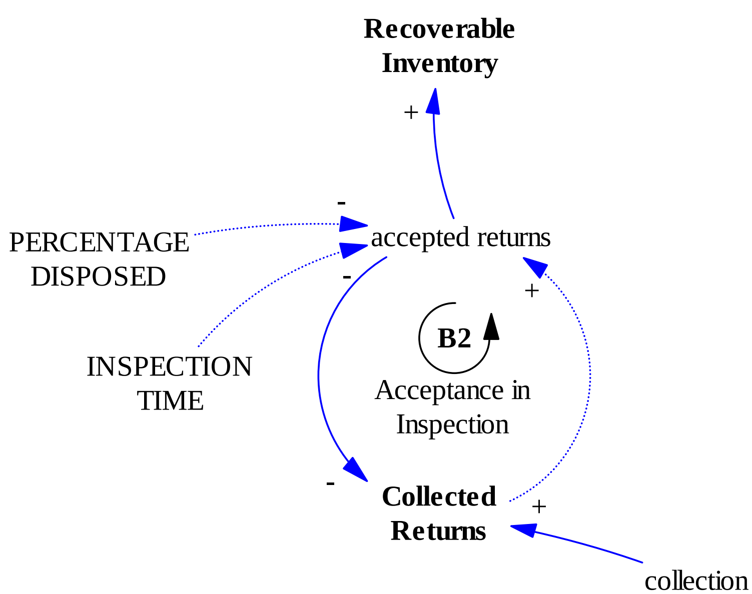


Figure 4.4: Acceptance in inspection feedback loop

The remanufacturing activity behaviour in the system is represented by two negative feedback loops, B3 and B4. These are shown in Figure 4.5. Remanufacturable items are stored as *Recoverable Inventory* from which items are used for remanufacturing purposes when necessary and stored as *Serviceable Inventory* in order to fulfil customer *demand*. An increase in the *Recoverable Inventory* level increases the *remanufacturing* rate, which in turn decreases the *Recoverable Inventory* level, thus forming the negative feedback loop B3. Similarly, in the negative feedback loop B4, an increase in *remanufacturing* increases the *Serviceable Inventory* level, which in turn decreases the level of *remanufacturing* activity. Thus, inventory levels have both positive and negative effects on the *remanufacturing* rate, which effectively controls the flow of remanufacturing items and achieves a balance in the inventory system. Moreover, *remanufacturing* flow is negatively affected by the *REPLENISHMENT FREQUENCY* of the inventory. Replenishment frequency represents the time taken to replenish remanufacturing orders and an increase/decrease in its value generally leads to a decrease/increase in the order size.

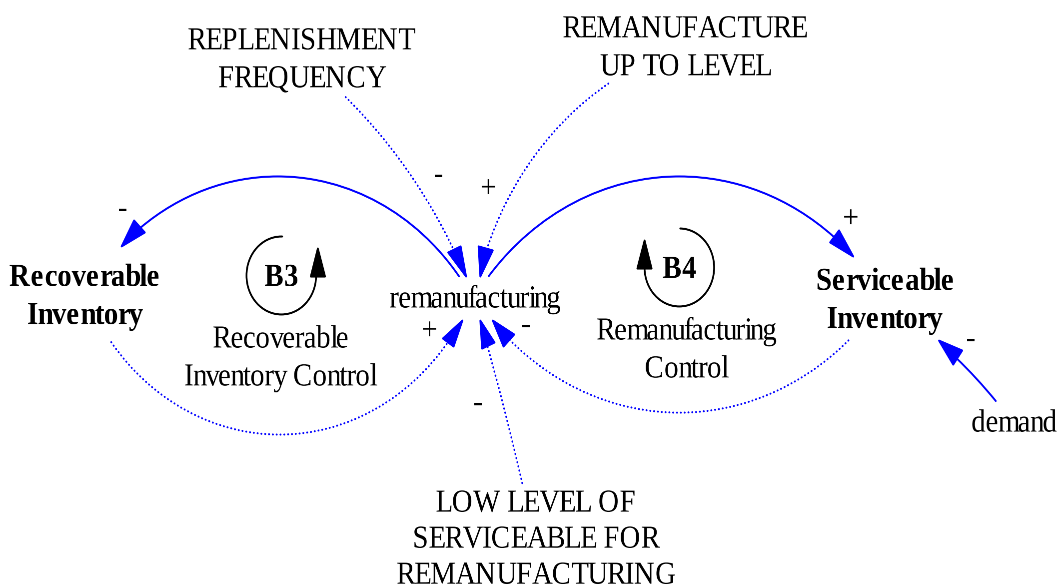


Figure 4.5: Remanufacturing feedback loops

In the system, remanufacturing, which is preferred to a more expensive production activity, occurs when necessary as a pull inventory policy is applied. Several studies have previously modelled push and pull inventory policies in a production and inventory system for remanufacturing (Kiesmuller 2003; van der Laan & Salomon 1997; van der Laan, Salomon & Dekker 1999). As shown in Figure 4.6, *REMANUFACTURE UP TO LEVEL* (*Sr*) and *LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING* (*sr*) are two variables that affect the *remanufacturing* rate and are used to implement a pull policy in the system. *Sr* represents the upper value limit for remanufactured batches, while *sr* represents the lower value for remanufactured batches as well as the level of a *Serviceable Inventory* at which a remanufacturing batch is required. *Sr* - *sr* represents the level of *Recoverable Inventory* for which it is possible to produce a remanufacturing batch.

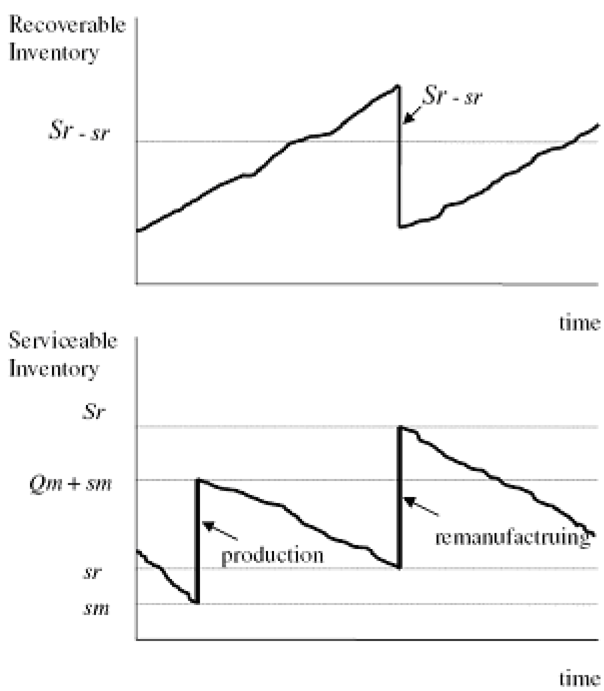


Figure 4.6: Usage of inventory in the system (adapted from van der Laan, Salomon and Dekker (1999))

A more detailed picture of the inventory pull policy is given in Figure 4.6, which shows the usage of inventory over time in a production and inventory system for remanufacturing. Figure 4.6 is similar to that developed by van der Laan, Salomon and Dekker (1999), who also did not consider disposal of recoverable inventory. The pull policy is represented by the *Recoverable Inventory* level. Only when this level reaches the difference (*Sr* - *sr*) and the *Serviceable Inventory* level is lower than *sr*, is it possible to produce a remanufacturing batch. Production activity is only used to increase the *Serviceable Inventory* level when the *Recoverable Inventory* level is lower than (*Sr* - *sr*) and the *Serviceable Inventory* level is lower than *sm* (the *Serviceable Inventory* level at which a production batch is required). This strategy increases the cost of the *Recoverable Inventory* but reduces the cost of the *Serviceable Inventory* which is usually more expensive. Moreover, remanufacturing is preferred to production activity, as *sm* is lower than *sr*.

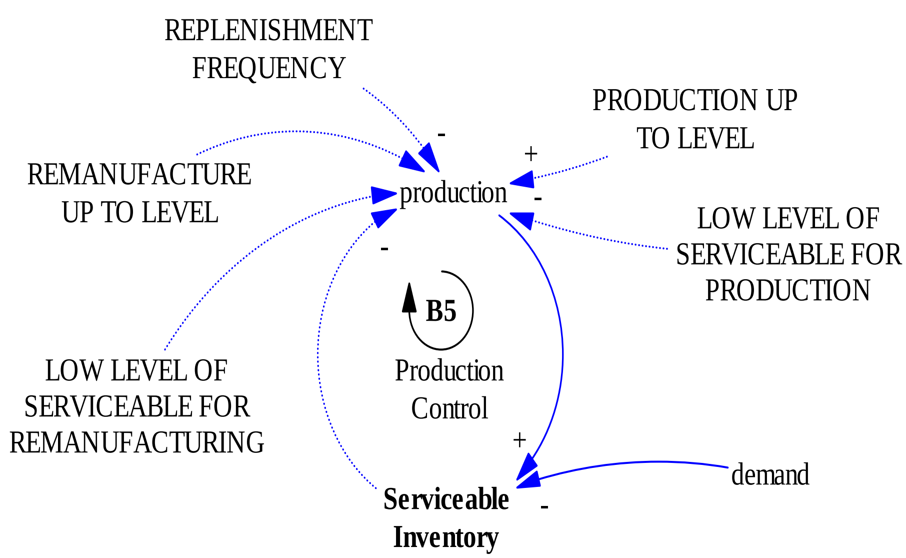


Figure 4.7: Production feedback loop

Produced items increase the *Serviceable Inventory* level in order to fulfil customer *demand*, as Figure 4.7 shows. Two additional variables that affect production flow are used to implement the pull inventory policy: *PRODUCTION UP TO LEVEL* (*Qm*), which is the upper value for production batches; and *LOW LEVEL OF SERVICEABLE FOR PRODUCTION* (*sm*). However, production flow is mainly affected by *Sr* and *sr*, because it is only when the *Recoverable Inventory* level is lower than *Sr* - *sr* and the *Serviceable Inventory* level reaches *sm* that a production batch is manufactured and stored in *Serviceable Inventory*. The negative feedback loop B5 thus creates a balance between *production* flow and the *Serviceable Inventory* level.

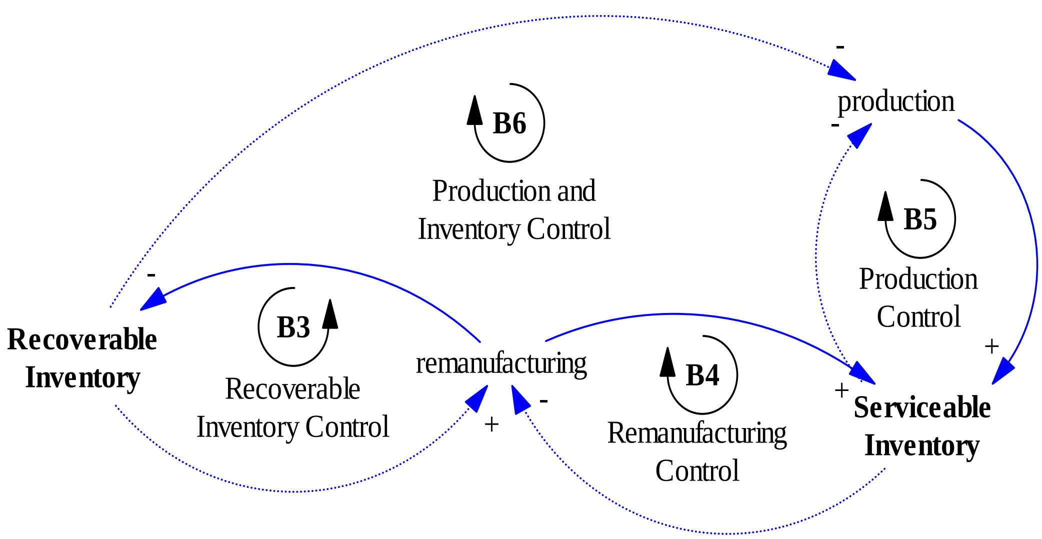


Figure 4.8: Production and inventory control within remanufacturing feedback loops

The negative loop B6 involves both the *production* and *remanufacturing* flows and both the *Recoverable* and *Serviceable Inventory* levels, as shown in Figure 4.8. A balance among these variables, which involves a control process between inventory levels and flow of items, is required in order to prioritise remanufacturing over production activity. For example, if the *Serviceable Inventory* level decreases, both the remanufacturing and the production activity should increase due to the two negative feedback loops B4 and

B5. However, if the *Recoverable Inventory* level is sufficient for the remanufacturing activity, the negative relationship between *production* and *Recoverable Inventory* generates a decrease in production activity. This leads to a system in which the *remanufacturing* flow is preferred to the *production* flow in order to generate products for the *Serviceable Inventory*.

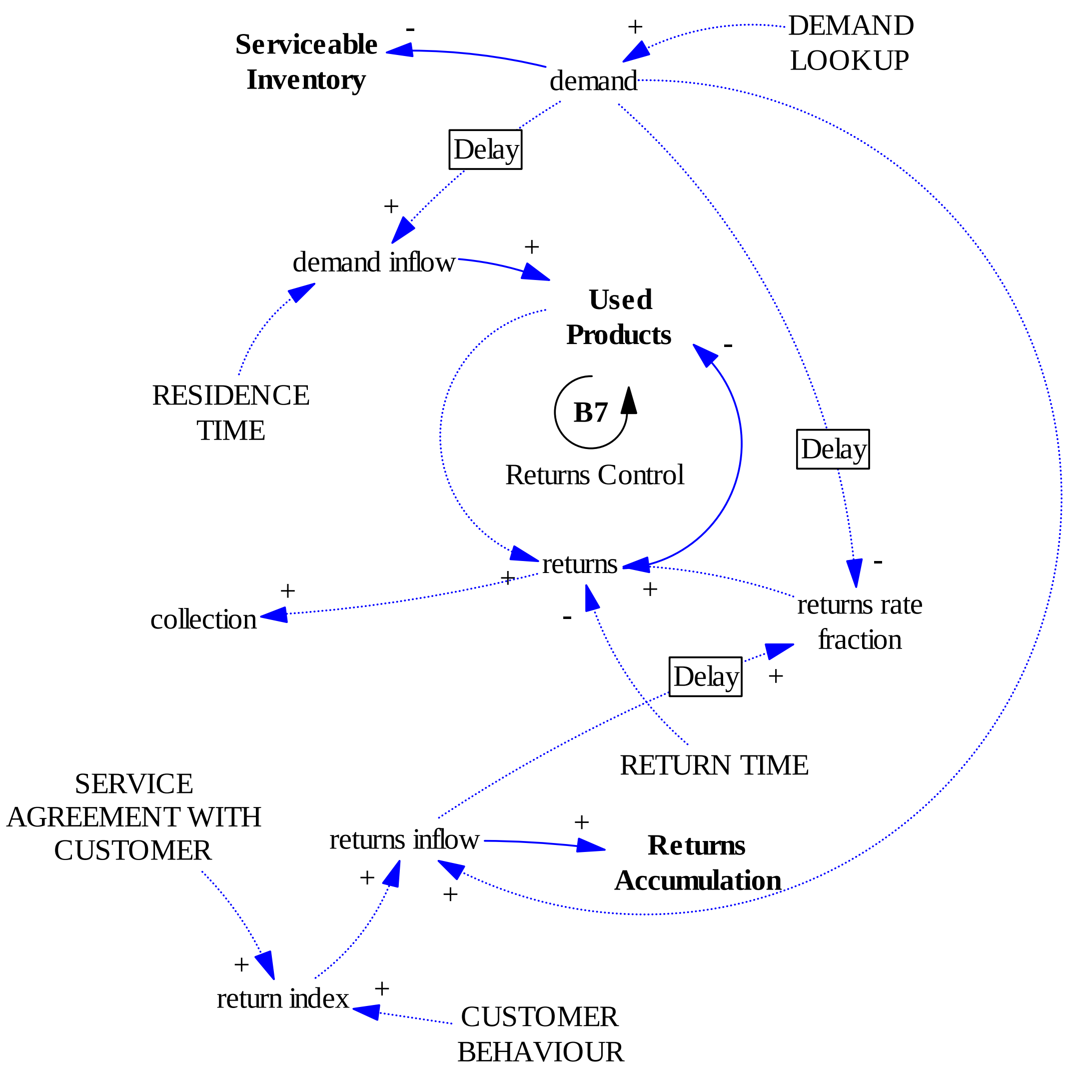


Figure 4.9: Returns control feedback loop

The behaviour of the negative feedback loop B7 (see Figure 4.9) is caused mainly by *Used Products* and *returns* as well as several variables representing the influence relationships between the forward and reverse logistics. The process starts with customer demand, which depletes *Serviceable Inventory* level. Product demand, which is considered equal to sales, is defined by external historical data represented by *DEMAND LOOKUP*. After a period of time or *RESIDENCE TIME*, products in use can be considered used products. This is represented by the flow between the rate of the variable *demand inflow* and the level of *Used Products*.

The variable *RESIDENCE TIME* is the average time for which a product stays with its customer before it is returned (Georgiadis, Vlachos & Tagaras 2006). This period of time varies for different kinds of products and different customer behaviours. This variability represents the uncertainty which affects the timing of returns in a closed loop supply chain. For this reason, in this model not all used products are considered to be returns but rather as possible returns after an average period of use that is dependent on the type of product. A portion of these used products become *returns*, which are consequently collected. This is represented by the physical flow in which *returns* deplete the *Used Products* level and the information flow between *returns* and *collection*. Furthermore, in this case the level of used products affects and controls the flow of returns, generating the negative loop B7, which characterises the possibility that not all used products are returned at the same time.

Uncertainty in the quantity of used products returned by customers negatively affects collection, remanufacturing, production planning and inventory control. For this reason, several variables, shown in Figure 4.9, are used to reduce the effect of uncertainty and set the quantity of returns. The *return index* is used to set the number of returns based on customer demand. The number of returns is represented by the *returns inflow* which is influenced by the *returns index* and *demand*. Two parameters influence the *return index*: *SERVICE AGREEMENT WITH CUSTOMER* and *CUSTOMER BEHAVIOUR*. The former defines the level of service agreement or incentives that the company offers to the customer at the end or during the use of the product in order to stimulate the return process. However, it could also represent the level of responsibility the company has towards the recovery of its own products. The latter parameter defines the attitude of the customers in returning used products and their response to company incentives aimed at increasing the return process. The relationships among these three factors are shown in Figure 4.10. The difficulty in obtaining and documenting real data has led to the use of a distributional form made on intuitive grounds. However, a similar approach to an influence analysis was presented by Georgiadis and Vlachos (2004b), who analysed different parameters such as market behaviour and the “green image” factor for products in different industries.

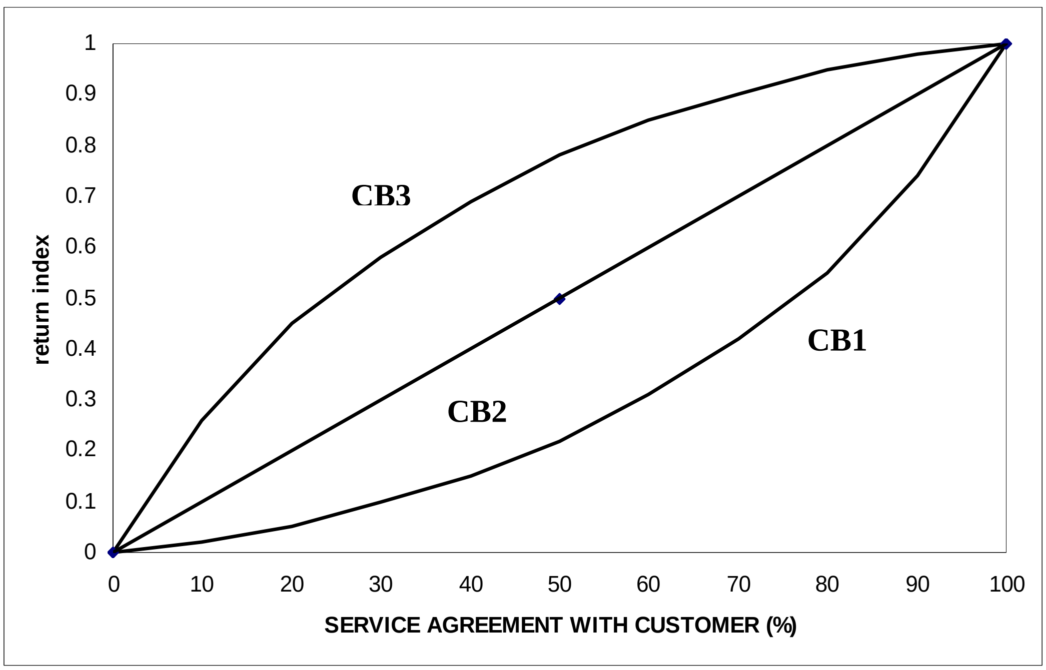


Figure 4.10: Relationship between *SERVICE AGREEMENT WITH CUSTOMER* and *return index* for various *CUSTOMER BEHAVIOURS*

In Figure 4.10 *return index* for a particular product is obtained from the level of service that a company offers to the customer to retrieve the product after its use. Therefore, the values of *SERVICE AGREEMENT WITH CUSTOMER* are between 0 and 100% which correspond to 0 and 1 of the *return index*, respectively. High values of service agreement are obtained by companies that offer incentives for the full return of sold products, for example, through leasing contracts (e.g. cars and photocopiers) or service at the end of the useful life of a product/component (e.g. single-use cameras and toner cartridges). Also included are companies that have full responsibility for recovery due, for example, to government environmental regulations. High values of service agreement correspond to high values of *return index*, for which it is assumed that almost all sold products are returned by customers. The minimum value corresponds to the kinds of products not involved in reverse logistics activity, particularly remanufacturing, entailing a zero return index and no efforts by companies to generate product recovery. Regarding the in-between values, the dependency between the index and service agreement depends on *CUSTOMER BEHAVIOUR* (CB).

A range of company incentives are used in practice to stimulate a desired customer behaviour in the area of product recovery (de Brito, Dekker & Flapper 2004), including: a deposit that must be paid when purchasing the product; free collection or repurchase of used products; a monetary incentive paid upon return of used products; and a trade-in that involves the possibility of obtaining a newer version of a product when the original product is returned. Currently, products designed for easier disassembly and clear information/advertising about reverse logistics activities and environmental responsibilities are being developed by companies in order to assure the return of used products. However, the sensitivity and reaction to such incentives depend on individual customer behaviour. To incorporate various possible customer behaviours in this study, three alternative relationships are assumed, which are represented in Figure 4.10. CB2 corresponds to a proportional relationship between *SERVICE AGREEMENT WITH CUSTOMER* and *return index*. In this case, it is assumed that customers respond proportionally to incentives and services offered by companies attempting to recover used products. The symmetric curves CB3 and CB1 correspond to a quicker and slower response from customers, respectively. Particularly in relation to CB3, it is assumed that the response of customers and consequently the associated *return index* changes quickly for low values of *SERVICE AGREEMENT WITH CUSTOMER* while it is almost the same for higher values. This is different for CB1 which becomes more acute for higher values of *SERVICE AGREEMENT WITH CUSTOMER*. This influence analysis is used to account for, as much as possible, the relationship between customer behaviour and quantity of returns.

4.2.3 Quantitative Modelling

Causal Loop Diagrams are a useful tool for representing the causal relationships and feedback processes within the systems. However, they suffer from a significant limitation in representing systems, regarding their inability to capture the stock and flow structure of systems (Sterman 2000). Indeed, all business and social systems contain a host of different asset stocks or accumulation of resources which change according to their physical inflows and outflows (Morecroft 2007). According to Morecroft, this stock and flow structure of systems reveals the operating details behind the causal influences or links defined in the Causal Loop Diagrams.

In SD the stock and flow structure of systems is represented through the SFD. Such a diagram is obtained by converting the feedback structure of the CLD into a stock and flow structure. This conversion involves the identification of stock, flow and auxiliary variables among the variables used to represent the CLD. A definition of the stock, flow and auxiliary variables was previously provided in Section 3.4.2. The objective in developing an SFD is to analyse and define the dynamic relationships among stock, flow and auxiliary variables through mathematical equations in order to run simulations of the model.

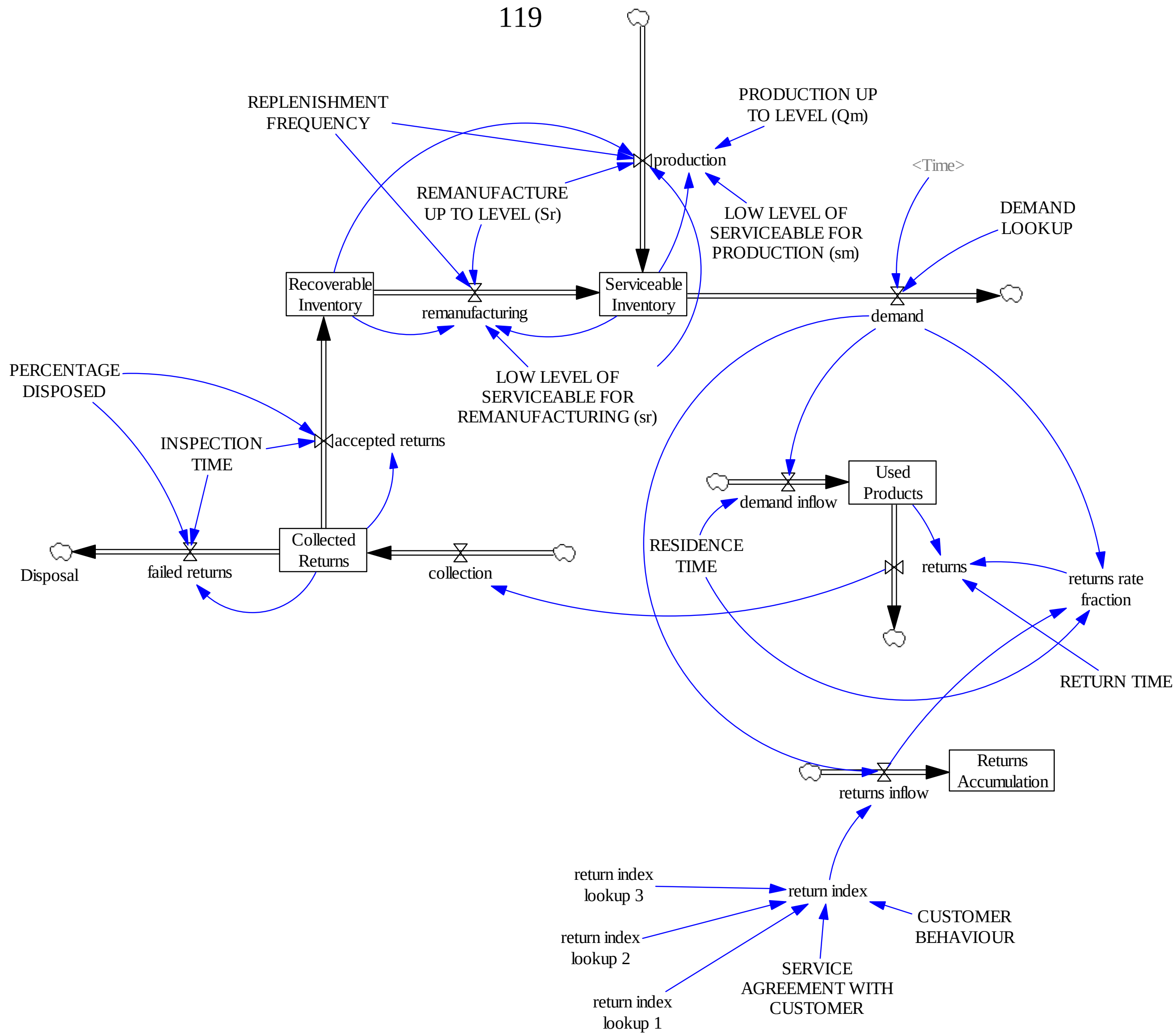


Figure 4.11: Stock and Flow Diagram

The SFD for the production and inventory system for remanufacturing whose CLD was shown in Figure 4.2 is presented in Figure 4.11. The rectangles represent stock variables which equate with accumulations of items, while the valves represent flow variables which correspond to the physical flow of items feeding or depleting the stocks. The physical flow of items is represented by a double line with arrows, while flow of information (i.e. connection among variables and their relationships for mathematical formulations) is represented by a single line with arrows. The auxiliary variables shown in upper case letters represent constants or exogenous inputs, while those in lower case letters represent converters used in calculations.

The dynamic relationships among the variables of the developed SFD for the production and inventory system for remanufacturing are defined by a set of mathematical equations. The main equations are shown in Table 4.1. The symbology and the form used for the equations follow the conventions of the simulation software used to build the model: Vensim PLE v5.6d. This provides a simple and flexible means of building simulation models from causal loop or Stock and Flow Diagrams (Ventana Systems Inc. 1999). The mathematical equations include several constant parameters or inputs. The latter correspond to the exogenous inputs of the SFD, which are represented in upper case letters, as well as to the initial values of the stock variables. Usually, when modelling a specific real system, the values of these parameters can be fine-tuned in order to reproduce the behaviour of the system. However, because in this study we are developing a generic SD model of a production and inventory system for remanufacturing, assumptions are used for the value of the parameters. Indeed, given the objective of running a simulation of this generic model to evaluate strategies, with a particular focus on the returns process, in order to improve the performance of the system, we believe that the intuitive understanding regarding the impacts of the structure of the model on its dynamic behaviour is more important than determining the exact value of the parameters. However, the assumptions used for the value of the parameters, which will provided for the sensitivity analysis of the model in Section 4.3.2, are set in order to correspond as much as possible to a meaningful concept based on real world situations. A detailed explanation of the equations and conventions used will be provided next.

Table 4.1: Formulation of the model

(1)	*Collected Returns = INTEG (collection – accepted returns – failed returns, 0)* Units: items
(2)	*collection = returns* Units: items/month
(3)	*demand = DEMAND LOOKUP(Time)* Units: items/month
(4)	*demand inflow = DELAY FIXED (demand, RESIDENCE TIME, 0)* Units: items/month
(5)	*DEMAND LOOKUP([(0,0) - (60,4000)] ,(0,359.82), (12,596.7), (24,1283.36), (36,1921.92), (48,2223.31), (60,2251.79))* Units: items/month
(6)	*accepted returns = (Collected Returns* (1 –PERCENTAGE DISPOSED)) / INSPECTION TIME* Units: items/month
(7)	*failed returns = (Collected Returns*PERCENTAGE DISPOSED) / INSPECTION TIME* Units: items/month
(8)	*production = IF THEN ELSE (Serviceable Inventory <= LOW LEVEL OF SERVICEABLE FOR PRODUCTION (sm) :AND: Recoverable Inventory < REMANUFACTURE UP TO LEVEL (Sr) - LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING (sr), (PRODUCTION UP TO LEVEL (Qm) – Serviceable Inventory) / REPLENISHMENT FREQUENCY, 0)* Units: items/month
(9)	*Recoverable Inventory = INTEG (accepted returns - remanufacturing, 0)* Units: items
(10)	*remanufacturing = IF THEN ELSE (Serviceable Inventory <= LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING (sr) :AND: Recoverable Inventory >= REMANUFACTURE UP TO LEVEL (Sr) - LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING (sr), (REMANUFACTURE UP TO LEVEL (Sr) - LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING (sr)) / REPLENISHMENT FREQUENCY, 0)* Units: items/month

Table 4.1 – continued from previous page

(11)	*return index = IF THEN ELSE (CUSTOMER BEHAVIOUR = 3, return index lookup 3 (SERVICE AGREEMENT WITH CUSTOMER), IF THEN ELSE (CUSTOMER BEHAVIOUR = 2, return index lookup 2 (SERVICE AGREEMENT WITH CUSTOMER), return index lookup 1 (SERVICE AGREEMENT WITH CUSTOMER)))* Units: dimensionless
(12)	*returns = (Used Products * returns rate fraction) / RETURN TIME* Units: items/month
(13)	*Returns Accumulation = INTEG (returns inflow, 0)* Units: items
(14)	*returns inflow = demand * return index* Units: items/month
(15)	*returns rate fraction = DELAY FIXED (returns inflow / demand, RESIDENCE TIME + 1, 0)* Units: dimensionless
(16)	*Serviceable Inventory = INTEG (production + remanufacturing - demand, 0)* Units: items
(17)	*Used Products = INTEG (demand inflow - returns, 0)* Units: items
(18)	*return index lookup 1([(0,0) - (100,1)] ,(0,0), (10,0.02), (20,0.05), (30,0.01), (40,0.15), (50,0.22), (60,0.31), (70,0.42), (80,0.55), (90,0.74), (100,1))* Units: dimensionless
(19)	*return index lookup 2([(0,0) - (100,1)] ,(0,0), (50,0.5), (100,1))* Units: dimensionless
(20)	*return index lookup 3([(0,0) - (100,1)] ,(0,0), (10,0.26), (20,0.45), (30,0.58), (40,0.69), (50,0.78), (60,0.85), (70,0.9), (80,0.95), (90,0.98), (100,1))* Units: dimensionless

Equation 1 below represents the dynamic behaviour of the stock variable *Collected Returns*. As previously mentioned in Section 3.4.2, the mathematical interpretation of the stock variables is an integral equation. Thus, the stock variable *Collected Returns* is defined by a time integral of the net inflow (*collection*) minus the net outflows (*accepted* *returns* and *failed returns*). The *INTEG* function represents the time integral, while zero is the assumed initial value of *Collected Returns* at time $t = t_0$:

$$Collected\ Returns\,(t) = \int_{t_0}^{t} (\ collection(t)\ -\ accepted\ returns(t) -\ \ failed\ returns(t))dt\ + \\ + Collected\ Returns\,(t_0\ ) \tag{10}$$

The *collection* flow (equation 2) is equal to the *returns* flow. This means that at time t, all returns follow a collection process: $collection(t) = returns(t)$. Infinite collection capacity is assumed as all the possible returns are collected. *Failed returns* at time t are equal to total *Collected Returns* times the *PERCENTAGE DISPOSED* divided the *INSPECTION TIME*. The percentage of disposed returns and the inspection time are considered constant due to the difficulty of representing and modelling the real dynamic variance for this factor which depends on product characteristics, company quality policy and inspection strategy; and this particular issue is not within the scope of this study. *Accepted returns* at time t are the *Collected Returns* that pass the inspection process. For this reason, the percentage of returns accepted for remanufacturing is 1 – disposal percentage. Equations 6 and 7 can thus be formulated:

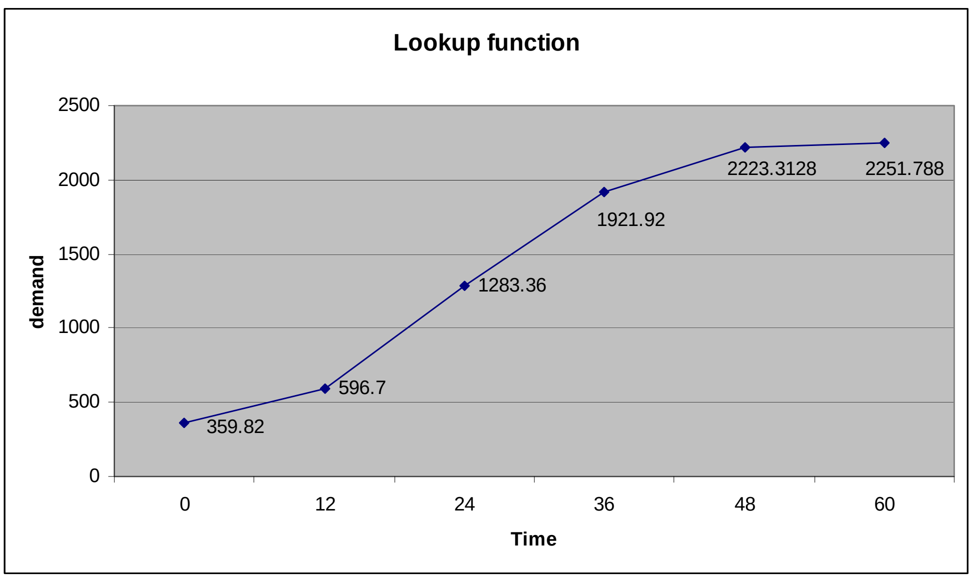
$$accepted\ returns\,(t) = \frac{Collected\ Returns(t) * (1 - PERCENTAGE\ DISPOSED)}{INSPECTION\ TIME} \tag{11}$$

$$failed\ returns\,(t) = \frac{Collected\ Returns(t) *\ \ PERCENTAGE\ DISPOSED}{INSPECTION\ TIME} \tag{12}$$

A functional relationship between two variables is used for the formulation of the *demand* at time t (equation 3). This is obtained using a lookup function which allows the definition of a customised relationship between a variable and its causes to be defined as a table of values. Specifically, an equation gives the value of *demand* at any time through a linear interpolation between the values specified in the table *DEMAND LOOKUP* (equation 5) as:

$$demand(t) = DEMAND\ LOOKUP\ (Time) \tag{13}$$

Table *DEMAND LOOKUP* is defined using historical data for product demand obtained directly from the Global Market Information Database (GMID), as it was not possible to collect such data from the companies used as case studies in this research. This database provides historical data, forecasts and statistical analysis for many countries worldwide on consumer goods in several industries, companies and brands.



Time (month)	demand
0	359.8
12	596.7
24	1283
36	1922
48	2223
60	2252

Figure 4.12: Demand function

The function that expresses the relationship between time and demand is shown in Figure 4.12. The numerical data were obtained from GMID and used as input for the model simulation. Specifically, they represent historical data on product demand for mobile phones for a particular company in Australia over a specific time period. In order to simplify the simulation analysis, they were considered in hundreds rather than thousands as expressed in the database. More details of how these data were obtained will be provided in the section that presents the model for the sensitivity analysis.

Demand inflow represents the flow of previously sold products currently in use which are now used products and possible returns after the *RESIDENCE TIME* has elapsed. In order to model this process the function *DELAY FIXED* is used (equation 4). This function returns the value of the input *demand* delayed by the delay time which in this case is the *RESIDENCE TIME*. Zero is the initial value of *demand inflow* at the start of the delay process: *demand inflow=DELAY FIXED (demand, RESIDENCE TIME, 0)*.

An *IF THEN ELSE* function and the logical operator *AND* are used to define the production quantity in the system (equation 8). In particular, they provide the number of production reorders during the simulation period. The logical expression defines the condition when the *Serviceable Inventory* level is less than or equal to the *LOW LEVEL OF SERVICEABLE FOR PRODUCTION* and also when the *Recoverable Inventory* level is less than *REMANUFACTURE UP TO LEVEL* minus *LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING*. If the condition is true, the expression returns a production reorder value equal to the ratio between *PRODUCTION UP TO LEVEL* minus the serviceable inventory on hand and the *REPLENISHMENT FREQUENCY*; otherwise the returned value is zero. A similar equation defines the remanufacturing quantity and the number of remanufacturing orders in the model. In this case, the condition requires that the *Serviceable Inventory* level is less than or equal to *LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING* and that *Recoverable Inventory* is greater than or equal to *REMANUFACTURE UP TO LEVEL* minus *LOW LEVEL OF SERVICEABLE FOR*

REMANUFACTURING. The possible returned values are a remanufacturing order equal to the ratio between *REMANUFACTURE UP TO LEVEL* minus *LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING* and *REPLENISHMENT FREQUENCY*, if the condition is true, or zero otherwise. *Recoverable* and *Serviceable Inventory* levels are defined in equations 9 and 16, respectively:

$$\begin{aligned} &Recoverable\ Inventory\ (t) = \int_{t_0}^{t} (\ accepted\ \ returns\ (t) -\ remanufacturing(t))dt + \\ &+ Recoverable\ Inventory\ (t_0\ ) \end{aligned} \tag{14}$$

$$\begin{aligned} &Serviceable\ Inventory\ (t) = \int_{t_0}^{t} (\ production(t) + remanufacturing(t) - demand(t))dt + \\ &+ Serviceable\ \ Inventory\ (t_0\ ) \end{aligned} \tag{15}$$

The variable *return index* is formulated through a combination of *IF THEN ELSE* and lookup functions (equation 11). This equation represents the tendency of a particular product to be returned by customers, considering individual customer behaviours and differing levels of service agreement or company incentives. The constant *CUSTOMER BEHAVIOUR* can assume three values, 1, 2 or 3, represented by the three different curves in Figure 4.10. In the function of value assumed by *CUSTOMER BEHAVIOUR*, *return index* is calculated through one of the lookup functions whose table of values is shown in equations 18, 19 and 20, respectively. These represent the lookup functions in which *return index* and *SERVICE AGREEMENT WITH CUSTOMER* are the dependent and independent variables, respectively.

The flow of actual returned items which are collected is represented as dynamic ratio between the portion of *Used Products* through the use of *a returns rate fraction* and the time required to return and collect the items (*RETURN TIME*) (equation 12):

$$returns(t) = \frac{(\ Used\ Products\ (t) *\ \ returns\ rate\ \ fraction\ (t)\ )}{RETURN\ TIME} \tag{16}$$

The variable *Used Products* is defined in equation 17:

$$Used\ Products(t) = \int_{t_0}^{t} (\ demand\ inflow(t) - returns(t))dt\ +\ Used\ Products(t_0\ ) \qquad (17)$$

Returns rate fraction represents the proportion or percentage of used products that are returned during the time period under consideration. Several authors, such as Kiesmuller (2003), Kiesmuller and Minner (2003) and Inderfurth (2005), use the returns rate variable in their models. In order to define the quantity of returns, they consider a returns rate to be the ratio between the average returns and the average demands. Consequently, the *returns rate fraction* in this model is represented as a dynamic ratio between *returns inflow* and *demand* (equation 15):

$$returns\ rate\ \ fraction\,(t) = \frac{returns\ inflow\,(t)}{demand(t)} \qquad (18)$$

A function *DELAY FIXED* is used to return the value of the input given by the previous ratio delayed by the *RESIDENCE TIME* plus one time period. The reason for this delay is due to the necessary time equivalence between the variables *returns* and *returns rate fraction*, as the accumulation of used products and the actual returns flow start one time period after the residence time. *Returns inflow* represents the expected returns of demand. A forecast of returns is obtained using the *return index* (equation 14):

$$returns\ inflow\,(t) = demand\ (t) *\ \ return\ index \qquad (19)$$

Finally, equation 13 defines the accumulation of returns from returns inflow through the time integral of the flow:

$$Returns\ Accumulation(t) = \int_{t_0}^{t} (\ returns\ inflow(t))dt + Retuns\ Accumulation(t_0\ ) \qquad (20)$$

4.3 Model Validation

Before we run a simulation of the model for evaluating and investigating strategies to improve the performance of the system, a validation analysis has to be performed in order to determine whether the model is suitable for this objective. In SD theory, model validation primarily involves the assessment of the structure and behaviour of the model in terms of being consistent with the available facts and descriptive knowledge of a real-world system (Morecroft 2007; Sterman 2000). Such assessment, as Sterman states, is useful to build confidence that a model is appropriate for its purpose.

Although the theoretical basis of the qualitative and quantitative modelling in this study was obtained from the literature review as well as from information gathered from the data collection, in order to develop a model which corresponds to a meaningful concept in the real world (Sterman 2000), we deemed it necessary to perform validation tests in order to define its capacity to reflect the structure and behaviour of a real process model.

The validation tests performed refer to the *direct structure tests* and *structure-oriented behaviour tests* (Barlas 1996) previously explained in Section 3.4.3. Specifically, for the *direct structure tests*, in which simulation was not involved, we engaged extreme condition tests in order to check whether each mathematical equation of the model made sense and was reasonable given the available knowledge of the real system. On the other hand, for the *structure-oriented behaviour tests*, which involve simulation of the entire model, we undertook behaviour sensitivity tests. These involve sensitivity analysis on particular parameters of the model aimed at comparing the high sensitivity of these parameters between the model and a real system.

First, a detailed description of the direct structure validation through extreme condition tests performed is provided. We then present a description of the sensitivity analysis.

4.3.1 Direct Structure Validation

Extreme condition tests were developed in order to perform a direct structure validation of the developed model. Specifically, under extreme conditions of the inputs values such as zero or infinity, the model should behave as a realistic system (Sterman 2000). Following Sterman, the validation was performed by means of tests for the model equations and particularly for the equations representing the flow variables. Extreme values were assigned simultaneously to all the input variables in order to analyse the value of the output, which should be compatible with a real system under the same extreme condition. The Reality Check function of the Vensim simulation was used to achieve this. This function allows modellers to test and compare models with real systems through “if this, then this” analysis.

Two types of equations are defined in Vensim for the Reality Check functionality: *Test Inputs* and *Constraints* (Ventana Systems Inc. 1999). The former specifies the conditions or circumstances under which a *Constraint* is binding—in other words it defines the “if this” analysis. The latter defines the consequences that should result from a given set of conditions and represents the “then this” analysis. A detailed description of this validation process is presented next.

The validation of the collection activity deals with the direct inspection of the model equations 6 and 7. Figure 4.13 shows the flow variables of the model involved in this analysis: *accepted returns* and *failed returns*. As Reality Check equations compare the behaviour of a model with the available knowledge from a real system, they require a different structure from the original SFD. Specifically, input variables for the equations under study are now considered as constants. In this case, *Collected Returns*, which was originally a stock variable, assumes extreme constant values for the test. In order to simplify the analysis, another assumption considers *INSPECTION TIME* to be equal to one time period and excludes it from the analysis. Indeed, under extreme conditions such as infinite or zero for the *INSPECTION TIME*, the system responds realistically going algebraically toward zero or infinite *accepted* or *failed returns*, respectively. Moreover, usually in a real system the inspection time can be linked to inspection capacity, which dimensionally has the units of measure *items/time* as a function of the product characteristics and company inspection strategy/policy. However, in this case an infinite inspection capacity was assumed (Section 4.2.1) in order to generalise the model for different products and industries.

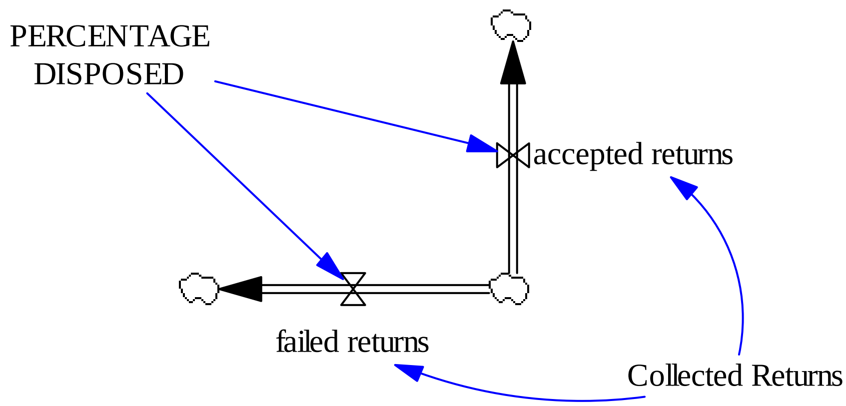


Figure 4.13: Collection activity for extreme condition test

The Reality Check equations require the development of a second diagram, as Figure 4.14 shows. This presents the relationship structure of the variables through which *Test Inputs* and *Constraints* equations are developed. Specifically, Level 1 identifies the *Test Inputs* equations while the *Constraints* are represented in Level 2. For example, the equations *0 collected items* and *no collection* are formulated as follows:

$$0\ collected\ items : TEST\ INPUT : Collected\ Returns = 0 \tag{21}$$

$$\begin{aligned} & no\ collection : THE\ CONDITION : 0\ collected\ items\ AND \\ & (max\ \%\ disposed\ OR\ \%\ disposed = 0) : IMPLIES : accepted\ returns = 0\ AND \\ & failed\ returns = 0 \end{aligned} \tag{22}$$

The first equation defines the condition for which zero collected items are generated when *Collected Returns* is equal to zero. This is a *Test Inputs* equation and it expresses the condition in the process. The second equation defines the expected consequence under a particular condition. In this case, if in the process there are zero collected items and either the maximum or minimum value of percentage of disposal, the output flow of accepted and failed returns should be equal to zero. This extreme condition is validated directly by the simulation software.

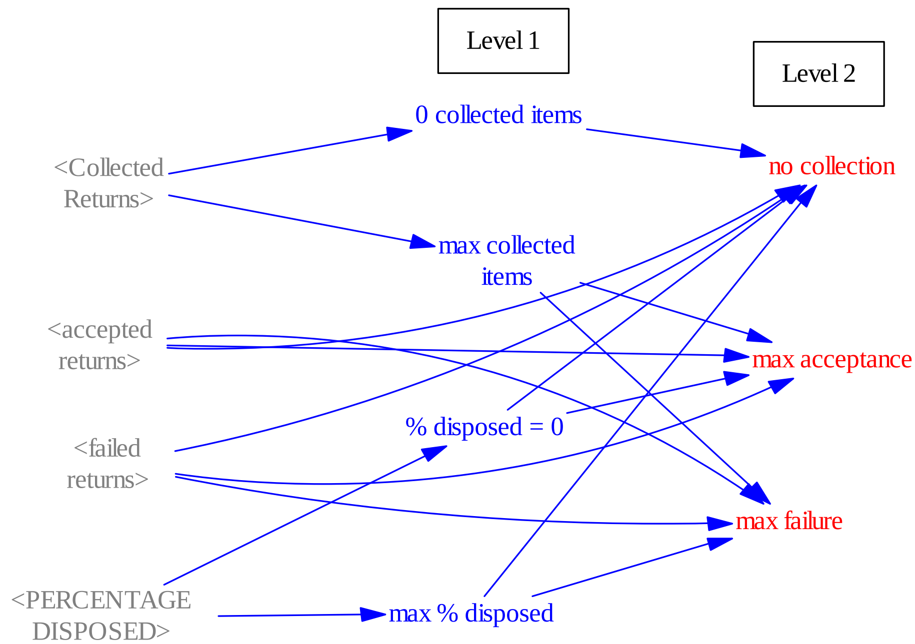


Figure 4.14: Relationships between *Test Inputs* and *Constraints*

The validation process for the collection activity considers several cases where extreme values are applied to the input variables. These cases apply either zero or infinite items for *Collected Returns* and either zero or 100% for *PERCENTAGE DISPOSED*. For any of these cases, the positive result is obtained and compared to the value of the output variables, which in this case are the flows of *accepted* and *failed returns*, to what would logically happen for a real system. In the first case, in which *Collected Returns* were set to zero, the result was of zero *accepted* and *failed returns* for any value of *PERCENTAGE DISPOSED*. This is valid for a real system in which the inspection process generates no output flow if no items are collected. The other cases follow the same logical pattern. For infinite number of *Collected Returns* and *PERCENTAGE DISPOSED* equal to either 100% or zero, the result was either of infinite *failed* or infinite *accepted returns*, respectively. This kind of analysis is supported by the simulation software, which ensures that all of the realistic consequences of the extreme conditions are observed through a *Violations of Constraints* report.

The validation for the equation representing the flow variable *remanufacturing* (equation 10) presented greater complexity due to the number of parameters involved and the equation structure. Figure 4.15 shows the variables involved for which *Recoverable* and *Serviceable Inventory* are now considered as constants. Moreover, similarly to the *INSPECTION TIME* for the previous validation, in this case the *REPLENISHMENT FREQUENCY* was considered equal to one time period and excluded from the analysis.

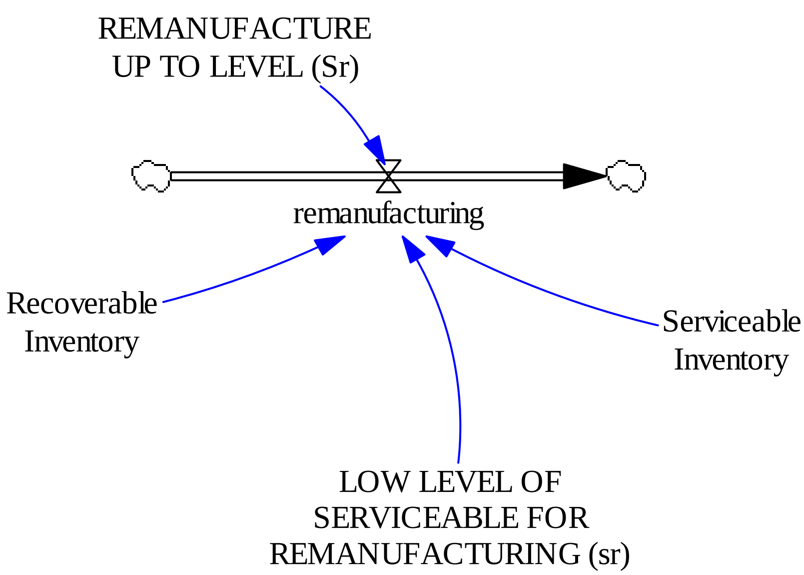


Figure 4.15: *Remanufacturing* for extreme condition test

Another assumption is based on the observation that $Sr - sr$ has to be greater than or equal to zero. This renders the model closer to a real system due to the impossibility in real life of having a negative value for remanufacturing orders. Moreover, it avoids the use of the extreme condition in which simultaneously sr is equal to infinity and Sr is equal to zero.

The first extreme condition set *Recoverable Inventory* as equal to zero and at the same time the other parameters (*Serviceable Inventory*, Sr and sr) equal to either zero or infinite. The result, similar to that of the system proposed by van der Laan, Salomon and Dekker (1999) (Figure 4.6), was zero remanufactured items. Indeed, without recovered items there is no remanufacturing independent of the number of serviceable items and the value of remanufacturing orders. The same result is obtained by setting *Recoverable Inventory* as equal to infinite, Sr as either equal to zero or equal to sr, and *Serviceable Inventory* as equal to infinite. In the first two cases, the system generates no remanufactured items as the value of remanufacturing orders is equal to zero, independent of the infinite number of recovered items. In the same way, infinite serviceable items do not require any remanufacturing activity.

The last extreme condition for equation 10 was obtained by setting both *Recoverable Inventory* and Sr as equal to infinite, and both *Serviceable Inventory* and sr as equal to zero. Under these conditions the system generates infinite remanufactured items. This is what should logically occur in a real system where serviceable inventory, which is only fed by remanufacturing, is equal to zero and the remanufacturing order is equal to infinite.

The validation process for the equation representing the flow variable *production* (equation 8) was similar to the analysis seen for the equation representing the flow variable *remanufacturing*. However, even if both the equations have the same structure, in this case more parameters are involved, as Figure 4.16 shows. For this reason, more

Test Inputs equations were required. Also in this case, assumptions were formulated in order to bring the model closer to a real system. The assumption that Qm - *Serviceable Inventory* on hand is greater than or equal to zero provides positive production reorder quantities and avoids the extreme case in which *Serviceable Inventory* on hand is infinite and at the same time Qm is equal to zero.

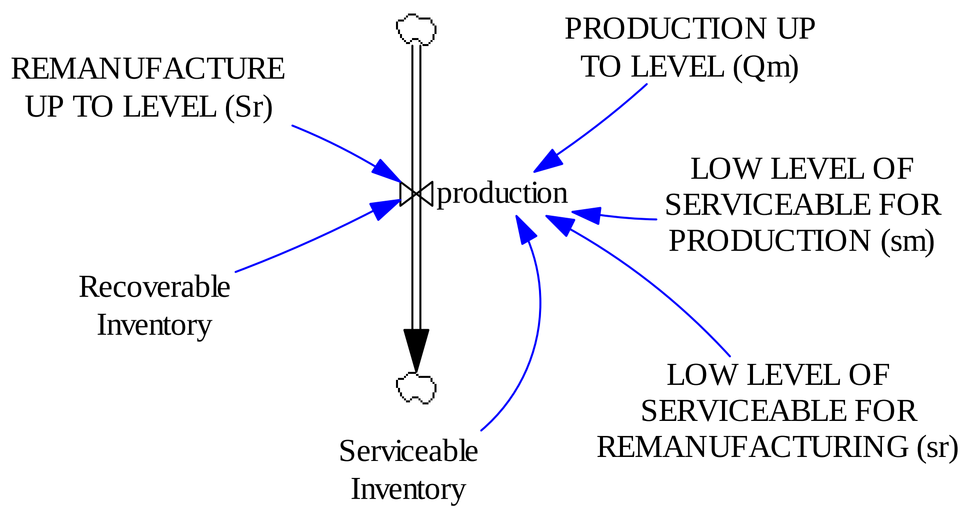


Figure 4.16: *Production* for extreme condition test

Through the validation process the production flow was assumed to have a value of zero or infinite under several extreme conditions for the parameters. These results follow both the behaviour of a real system and the conclusions presented in research conducted by van der Laan, Salomon and Dekker (1999) (Figure 4.6) who, however, consider a fixed production order (Qm - sm) rather than a production reorder (Qm - *Serviceable Inventory* on hand).

Assigning simultaneously the same value of either zero or infinity to Qm and *Serviceable Inventory*, then the production is equal to zero as the production reorder quantity is equal to zero, independent of the values of the other parameters. For infinite production reorder quantities (Qm = infinite and *Serviceable Inventory* = zero), the system generates infinite production when it is not possible to generate remanufacturing orders (*Recoverable Inventory* = 0, Sr = infinite and sr = 0). In this case, logically production assumes an infinite value as the shortage of serviceable items pulls the only available activity generated by infinite production reorder quantities.

If the system can generate remanufacturing orders (Sr = infinite, sr = zero and *Recoverable Inventory* = infinite), then production is equal to zero. This is due to the preference within the system for using remanufacturing instead of the more expensive production activity. In order to match the last case with a real system and the knowledge obtained from the literature, a positive value for remanufacturing orders ($Sr - sr$ is greater than zero) is assumed. This makes available the remanufacturing activity and avoids the extreme case in which at the same time Sr is equal to zero and sr is equal to infinity.

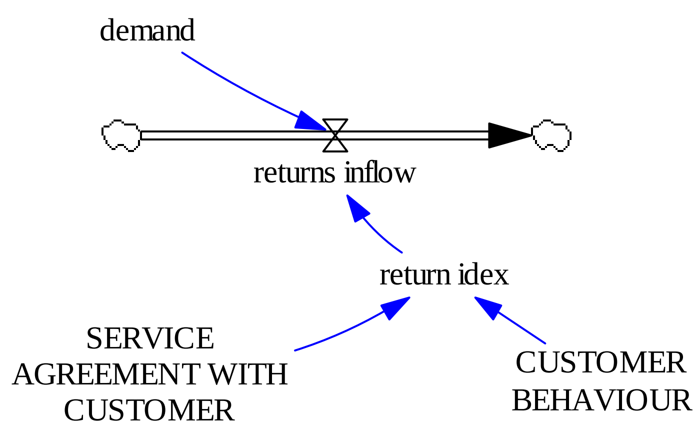


Figure 4.17: *Returns inflow* for extreme condition test

The validation process of the equation representing the flow variable *returns inflow* (equation 14) involved the parameters shown in Figure 4.17. Specifically, *Demand* was considered to be constant and *CUSTOMER BEHAVIOUR* was deemed not to affect the validation analysis. This last observation is due to the particular relationship assumed among the three parameters *return index*, *SERVICE AGREEMENT WITH CUSTOMER* and *CUSTOMER BEHAVIOUR* (Figure 4.10). This relationship entails that extreme values of service agreement correspond to the extreme values of *return index* for any value of customer behaviour.

For the extreme condition in which *demand* is assumed to have a value equal to zero, the output *returns inflow* is logically assumed to be equal to zero independent of the value of *return index*. This result is valid for a real system in which no sold products means there will be no possible returns. Conversely, if *demand* assumes an infinite value and at the same time there is a full *SERVICE AGREEMENT WITH CUSTOMER* (100%), which in turn generates a maximum *return index* value (1), then *returns inflow* is equal to infinity. This result is valid for a real system in which infinite sold products through, for example, leasing contracts can generate the return of all sold products, and thus infinite possible returns. Differently, infinite sold products with no service agreement can generate any number of possible returns.

The last extreme condition test concerns the equation representing the flow variable *returns* (equation 12). The parameters involved are shown in Figure 4.18. *Used Products*, *demand* and *returns inflow* were considered as constants and the parameter *RETURN TIME* was considered equal to one time period and excluded from the analysis. Moreover, it was assumed that *demand* is greater than zero. Indeed, if *demand* is equal to zero, the returns rate is infinite. However, zero *demand* entails zero *Used Products* and zero *returns inflow*, so that either the system matches the reality with zero returns due to there being zero used products, or it generates an indeterminable case where *returns rate fraction* is equal to zero divided by zero. For this reason, the minimum extreme value considered for *demand* is one. Another important observation is that all of the realistic results were obtained independently of the value assumed for the *RESIDENCE TIME*.

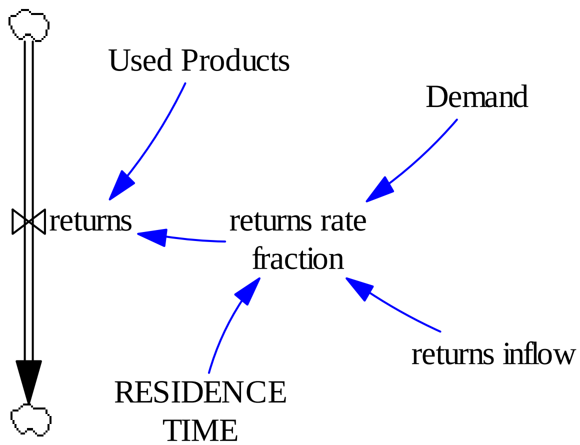


Figure 4.18: *Returns* for extreme condition test

Under the extreme conditions, the system generates *returns* equal to zero when either *Used Products* or *returns inflow* is equal to zero, independent of the other parameters. This is valid for a real returns process in which zero used products or zero possible returns entail no returns. Alternatively, if at the same time *Used Products*, *returns inflow* and *demand* assume an infinite value, the system generates infinite *returns*. This is due to the maximum value assumed for the *returns rate fraction*, which in this case could be considered equal to 100%. Similarly, for a real system in which the returns rate is equal to 100%, all used products become returns. Similar realistic results were obtained in the case in which *demand* assumed the minimum extreme value. In this case, the *returns rate fraction* assumes its maximum value (*returns inflow* is equal to infinite), which could be considered equal to 100%, which in turn generates a number of *returns* that is equal to the number of *Used Products*. This is valid for a real system in which only the accumulation of possible returns or used products can become effective returns as it is not possible to have more returns than used products.

4.3.2 Sensitivity Analysis

Following the direct structure validation through extreme condition tests, we validated indirectly the entire structure of the model through sensitivity analysis. This behaviour sensitivity test, particularly parameter sensitivity, consists of determining those parameters to which the model shows high sensitivity and comparing this high sensitivity between the model and the real system (Barlas 1996). Sensitivity analysis also tests the robustness of the model conclusions to particular assumptions (Sterman 2000). This means that the sensitivity of the model to changes of value for particular parameters should generate changes in the numerical value of the results or in behaviour patterns which are similar to what is observed in a real system and in line with the purpose of the model.

The parameters chosen to run the sensitivity analysis were *RESIDENCE TIME*, *SERVICE AGREEMENT WITH CUSTOMER*, *CUSTOMER BEHAVIOUR*, *PERCENTAGE DISPOSED*, *REMANUFACTURE UP TO LEVEL* (*Sr*), *PRODUCTION UP TO LEVEL* (*Qm*), *LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING* (*sr*) and *LOW LEVEL OF SERVICEABLE FOR PRODUCTION* (*sm*). The choice of these parameters was based on the high level of their influence on the dynamic behaviour of the system as well as the uncertainty around the most suitable values to be used in the model. Specifically, the first three parameters define the timing and quantity of returns, and have a high degree of influence on the dynamic behaviour of the system, particularly the returns process. The other parameters characterise the company strategy and policy in inventory control and inspection activity, which, because of the generality of the model, are affected by uncertainty in terms of determining their reasonable values for use in the model.

The base scenario for establishing the values of the model parameters involved the use of several assumptions aimed at ensuring the model corresponds as much as possible to a meaningful representation of the real world. Such assumptions reflect the theoretical basis drawn from the literature review and to a degree information obtained through the data collection. Indeed, the generic models based on remanufacturing and closed loop supply chains presented in the literature use several assumptions in relation to the values of the model parameters. For this reason, we deemed it appropriate to use similar assumptions for the purposes of the sensitivity analysis.

In setting the values of the parameters, historical data on product demand for mobile phones in Australia were used as input for the simulation in order to simulate *demand*. The data, previously presented in Section 4.2.3 for the table *DEMAND LOOKUP* (Figure 4.12), were extrapolated from the GMID database. They were obtained through a multiplication of the total demand data for the product and the percentage of market share of a particular company over the past six years (from 2002 to 2007 inclusive). However, in order to simplify the simulation analysis, this real data were considered in hundreds rather than thousands as expressed in the database. *INSPECTION TIME*, *REPLENISHMENT FREQUENCY* and *RETURN TIME* were set to one month. It was assumed that all returns collected in a given month are inspected within that same month, the remanufacturing orders and the production reorders are replenished monthly, and that there is a monthly collection of returns. The initial values at the beginning of the simulation horizon for the stock variables were set to zero (Georgiadis & Vlachos 2004b) for *Collected Returns*, *Recoverable Inventory* and *Used Products*, while 2,000 items were set for the *Serviceable Inventory*. *PERCENTAGE DISPOSED* was set at 0.1 (10%), 500 items for *LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING* (*sr*), 4,000 items for *REMANUFACTURE UP TO LEVEL* (*Sr*), 4,000 items for *PRODUCTION UP TO LEVEL* (*Qm*), 300 items for *LOW LEVEL OF SERVICEABLE FOR PRODUCTION* (*sm*) and 18 months for the *RESIDENCE TIME*. *CUSTOMER BEHAVIOUR* was set at 2. with a proportional relationship between *return index* and *SERVICE AGREEMENT WITH CUSTOMER*, which in turn assumed a value equal to 50%.

These parameter values chosen for the base scenario should be compatible with a real system. For example, a mobile phone is a product that presents an average residence time of around 18 months and a lifetime of 3–4 years (AMTA 2008; Georgiadis, Vlachos & Tagaras 2006). Moreover, the use of historical real data for the *demand* assists in setting the values for the factors involved in the inventory control activity (Sr, sr, Qm and sm), which regardless are tested through the sensitivity analysis to resolve the uncertainty around their value for use in the model. However, the generality of the model provides the opportunity to tune and customise the values chosen for the basic scenario within different kinds of products and different industries.

The simulation horizon was set to 60 months with a time step of one month. The effect of changes in the *RESIDENCE TIME*, specifically for 12, 18 and 24 months, on the returns process, keeping the other parameters constant to the basic scenario, is shown in Figure 4.19.

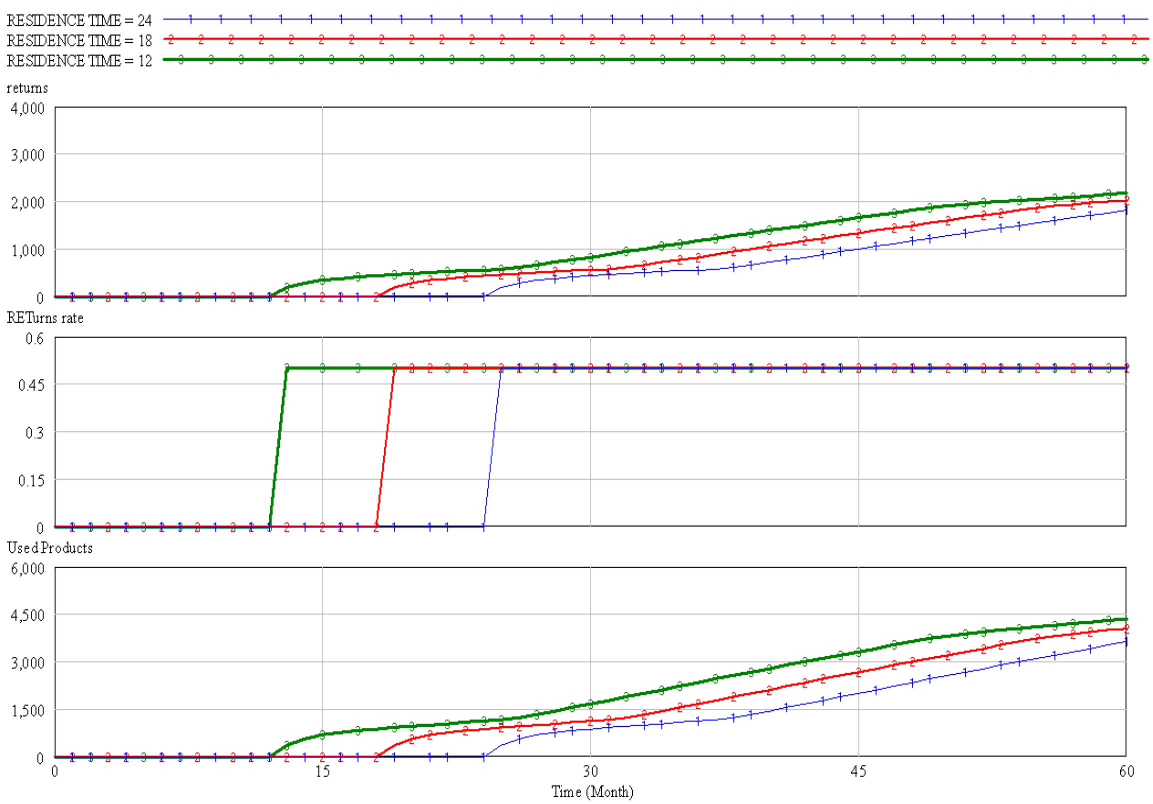


Figure 4.19: Effect of *RESIDENCE TIME* on the returns process

Changes in the *RESIDENCE TIME* do not affect the behaviour of the system as the three curves for each of the three variables follow the same trend. However, an increase in the *RESIDENCE TIME* produces a delay in the start of the returns process, which in turn generates a lower quantity of possible returns and consequently a lower quantity of effective *returns*. In a previous study, this has already been observed, as products with shorter residence times have a higher quantity of returns and therefore the potential for more profitable remanufacturability (Georgiadis, Vlachos & Tagaras 2006).

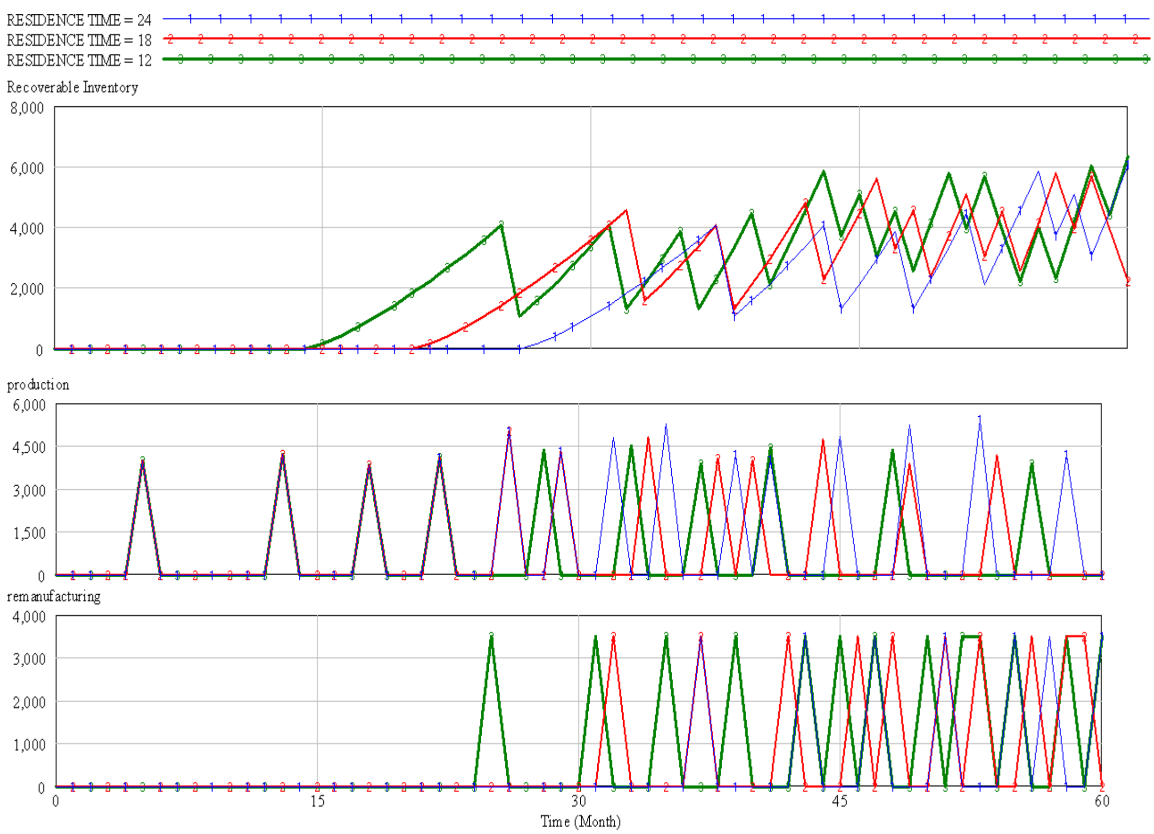


Figure 4.20: Effect of *RESIDENCE TIME* on production/remanufacturing activity

The last observation is confirmed by the results shown in Figure 4.20, which presents the effect of changes in the *RESIDENCE TIME* on factors involved in the production and inventory control activity within remanufacturing. In this case, the results show some changes in the behaviour of the system. Increasing the *RESIDENCE TIME* decreases the remanufacturing activity, as is evident in Figure 4.20, which shows a lower number of remanufacturing orders and consequently a greater number of production reorders. Indeed, the remanufacturing activity starts only when enough *Recoverable Inventory* is available to generate a remanufacturing order and, as is shown, this is faster for lower *RESIDENCE TIME*.

The sensitivity analysis regarding the behaviour of the system changing the value of the parameters *SERVICE AGREEMENT WITH CUSTOMER* and *CUSTOMER BEHAVIOUR* was obtained by setting the two parameters at several values. Figure 4.21 shows that, unexpectedly, the behaviour of the system is not excessively sensitive to changes of value in the two parameters. Increasing the incentives or service agreement that companies offer customers to generate the returns process of used products leads to only a small increase in both the quantity of *returns* and the average quantity of *Recoverable Inventory*. The numerical data shows an average quantity of 777 and 701 items for *returns* when service agreement is equal to 100% and 30%, respectively. In contrast, *Recoverable Inventory* is almost the same (1,900 items) in both cases. Similar results were obtained assuming an increase in responses from customers to company incentives. Specifically, the average quantity of *returns* increased from 665 to 767 items when the value of *CUSTOMER BEHAVIOUR* is equal to 1 and 3, respectively. *Recoverable Inventory* increased from 1,891 to 2,141 items.

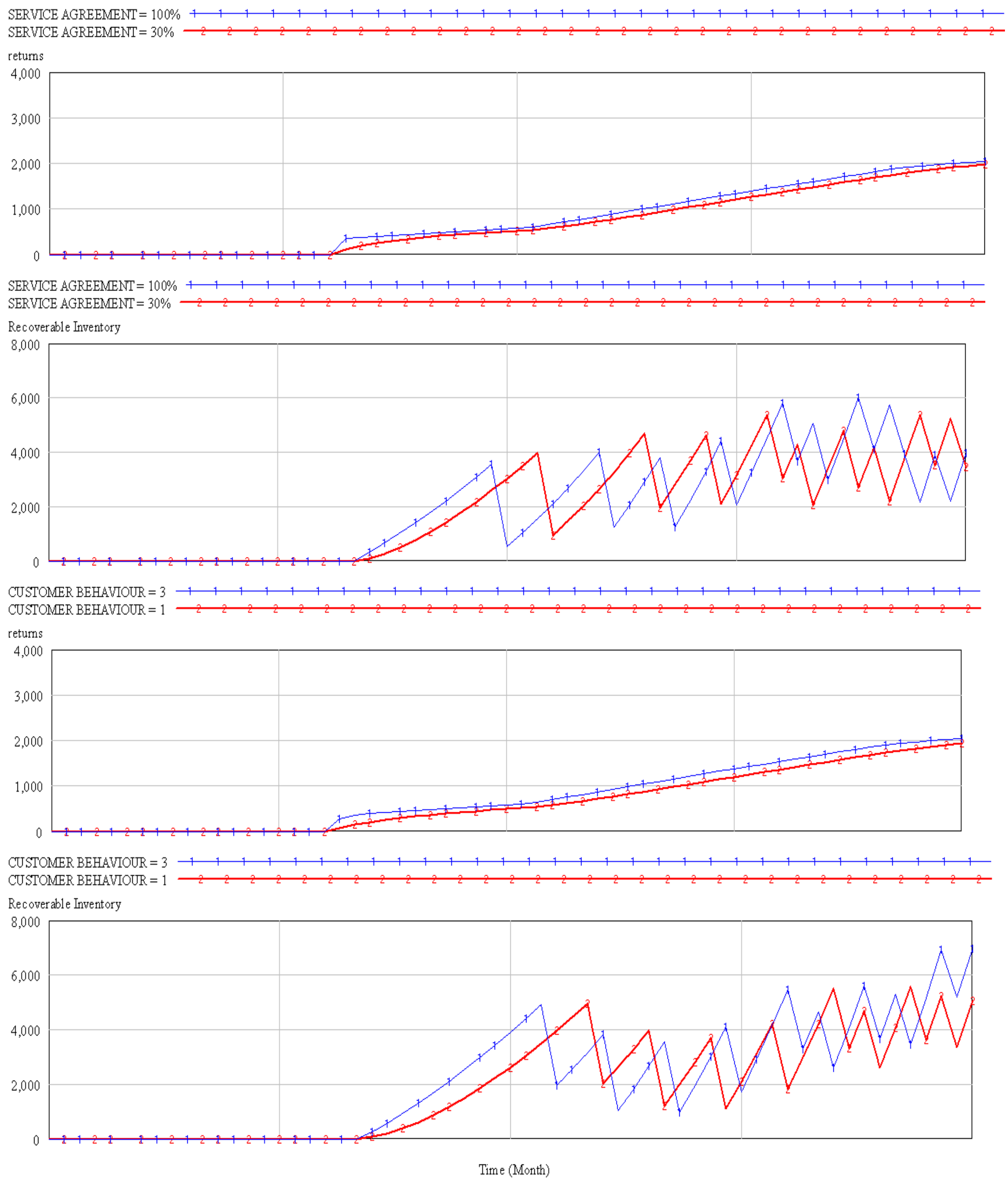


Figure 4.21: Effect of *SERVICE AGREEMENT WITH CUSTOMER* and *CUSTOMER BEHAVIOUR*

This particular behaviour of the system is due to the presence in the model of an accumulation of possible returns or *Used Products*. Specifically, the quantity of *returns* is obtained through the multiplication of the *returns rate fraction* by the accumulation of possible returns (*Used Products*). The latter increases in the case of a low percentage in incentives or service agreement offered to customers, as Figure 4.22 shows. However, this accumulation is due to the *RESIDENCE TIME* also. For this reason, the analysis suggests that joint changes in both parameters *RESIDENCE TIME* and *SERVICE AGREEMENT WITH CUSTOMER* could have a greater effect on the returns process and consequently on the production and inventory system for remanufacturing than changes only to the latter parameter.

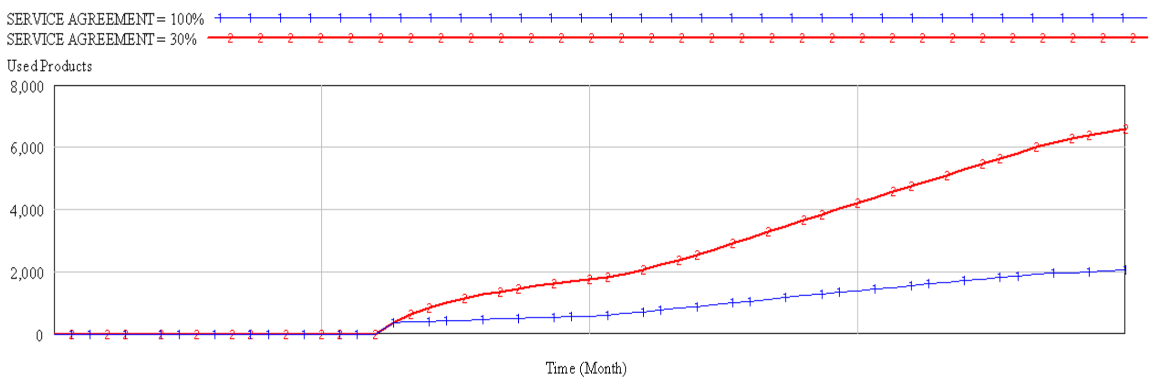


Figure 4.22: Effect of *SERVICE AGREEMENT WITH CUSTOMER* on *Used Products*

The last observation is supported by Figure 4.23, which shows that an increase in company incentives and a simultaneous decrease in the *RESIDENCE TIME* leads to an increase in the quantity of *returns*. Specifically, the average quantity of *returns* increases from 700 items to 1,210 items. This confirms that the profitable remanufacturability of a product—and in turn the need to increase the use of cheaper remanufacturing as a substitute for the more expensive production activity—depends on both the quantity and timing of returns. Indeed, in the real world, products and components such as single-use cameras and toner cartridges are good examples of profitable remanufacturability

(Georgiadis, Vlachos & Tagaras 2006). It is also well known that these kinds of products are characterised by a low residence time and high incentives for the return process.

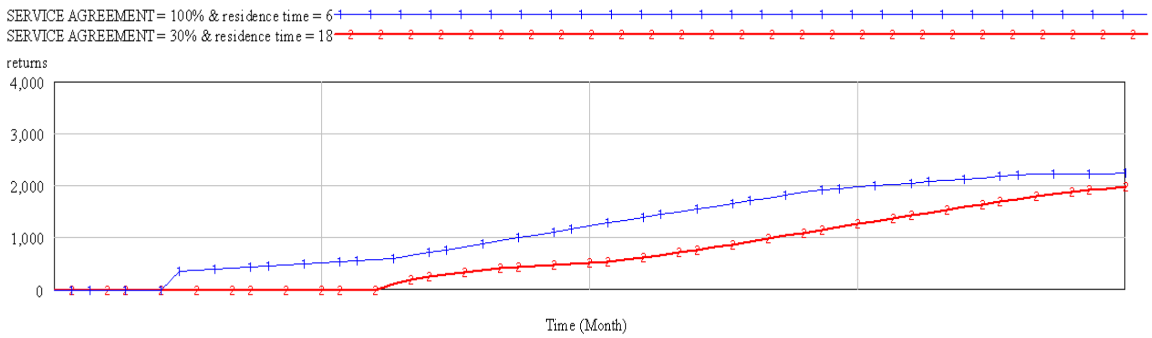


Figure 4.23: Effect of *SERVICE AGREEMENT WITH CUSTOMER* and *RESIDENCE TIME*

The analysis of the effects that the changes in the *PERCENTAGE DISPOSED* (D%) have on the system involved the use of three values for the parameter, 10%, 40% and 60%, keeping the other parameters constant to the basic scenario. This parameter is strongly influenced by the company policy applied in the quality control activity and in particular by the uncertain quality of returns. Low values for this parameter are preferred as they generate higher numbers of remanufacturable items and decreased disposal activity. For these reasons, the chosen values for the analysis involved two cases in which the D% is lower than 50% of returns (10% and 40%) and one case in which it is higher (60%). Another case is also added, specifically the extreme case of 95% of disposal, in order to understand and evaluate better the dynamics of the system. As the percentage of disposal is a factor involved mainly in the production and inventory control activity for remanufacturing, it does not affect the sensitivity of the system in the returns process. Figure 4.24 confirms this observation, showing curves exactly equal if the value of the parameter changes.

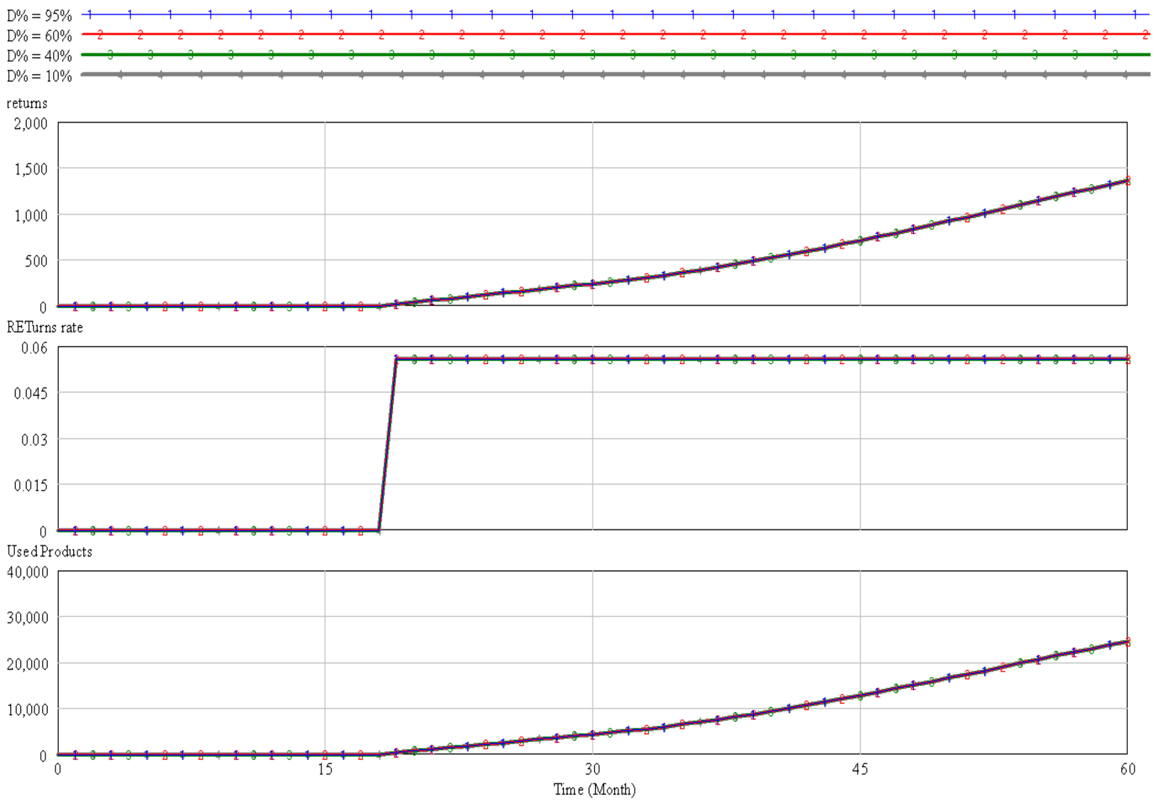


Figure 4.24: Effect of *PERCENTAGE DISPOSED* on the returns process

Changes in *PERCENTAGE DISPOSED* affect the variables involved in the production and inventory control activity for remanufacturing, as Figure 4.25 reveals. An increase in the value of this parameter generates lower remanufacturability in the system. This is due to the lower quantity of *Recoverable Inventory*, which reduces the number of potential remanufacturing orders. Specifically, the system generates no remanufacturing activity if almost all returns (95%) are disposed of.

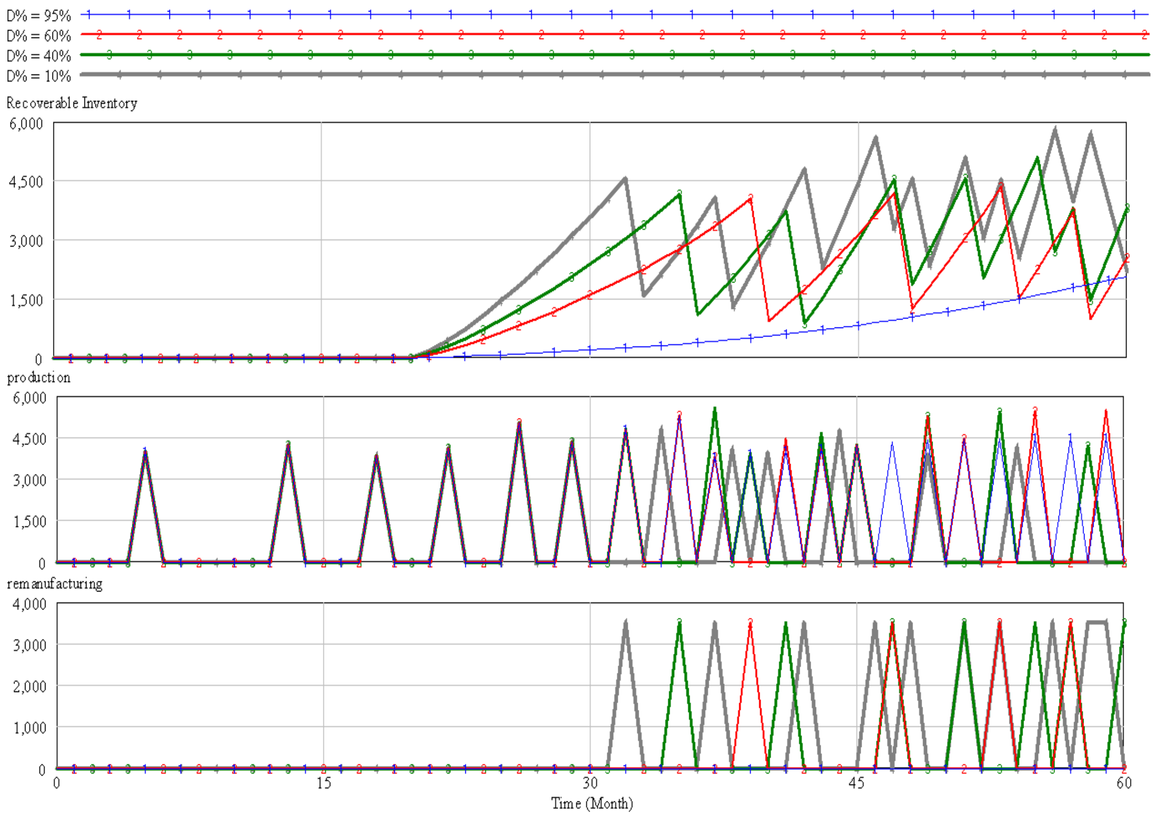


Figure 4.25: Effect of *PERCENTAGE DISPOSED* on production/remanufacturing activity

Regarding the parameters that characterise the inventory control activity, the first analysis involved simultaneous changes of both parameters Sr and sr from the respective values chosen for the base scenario. Table 4.2 shows the combinations of the two parameters used for the analysis.

Table 4.2: Combinations of Sr and sr

Combination	Sr **(items)**	sr **(items)**
1	4000	500
2	5000	500
3	4000	400
4	3000	500
5	4000	600

Combination 1 uses the values of the two parameters previously assumed for the base scenario, while combination 2 and 3 utilise an increase in the remanufacturing order quantity through an increase in Sr and a decrease in sr, respectively. However, sr has to be higher than sm in order to have a system that prioritises remanufacturing over production activity. In combinations 4 and 5 the remanufacturing order quantity is decreased through a reduction of Sr and an increase in sr respectively.

The production and inventory system for remanufacturing is sensitive to changes in the parameter Sr and this sensitivity is comparable to a real system, as Figure 4.26 shows. Specifically, combinations 2 and 4 are used to increase and decrease, respectively, 1,000 items in the remanufacturing order quantity. In these cases, the analysis shows that the decrease in the remanufacturing order size leads to an increased number of orders for remanufacturing. The data present 14 orders for combination 4 against 8 orders for combination 2. The *Recoverable Inventory* drops from an average quantity of 1,964 items (combination 2) to 1,570 items (combination 4). *Serviceable Inventory* drops from an average quantity of 1,073 items (combination 2) to 765 items (combination 4). These results reflect operations management theory which posits that in an inventory system decreasing the order size means the number of orders increases and the inventory level drops (Heizer & Render 2006). However, an analysis of the availability of serviceable stock is required in order to evaluate the effect of the changes in Sr on the service level to the customer. The total stockout quantity, represented by the negative quantity of *Serviceable Inventory*, is higher (13,274 items) for the lower remanufacturing order size as in combination 4. This value is 8,600 for combination 2.

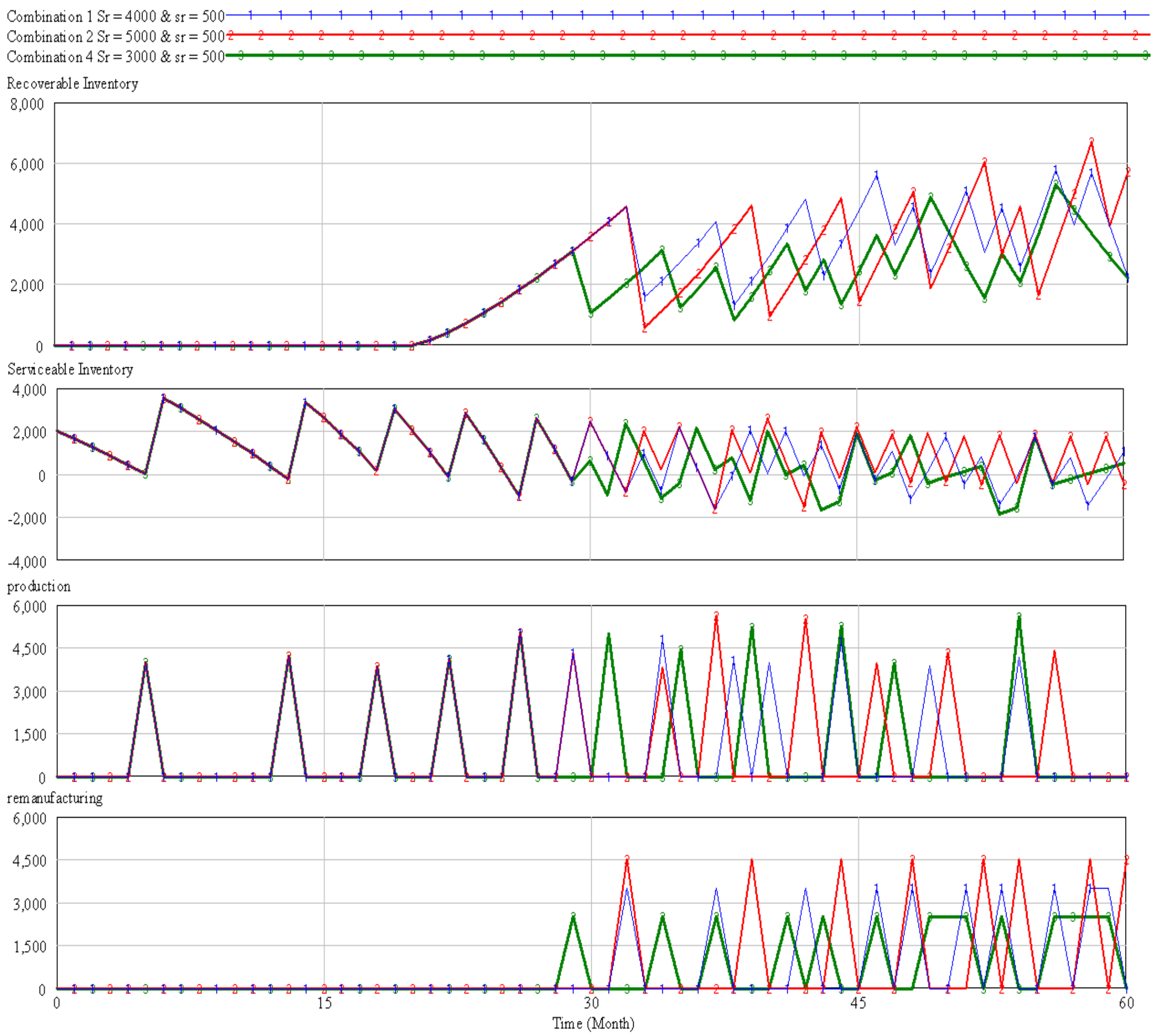


Figure 4.26: Effect of Sr

Different results were obtained by both increasing and decreasing the remanufacturing order value through the changes in the parameter sr. The use of combinations 3 and 5 resulted in a lower sensitivity of the system to the changes in this parameter. Specifically, the variables *Serviceable Inventory*, *remanufacturing* and the stockout did not display relevant changes in average and total quantity. This is due to the lower impact that sr has on the increase/decrease in the remanufacturing order as combinations 3 and 5 generate a change in the latter of only 100 items. However, increasing sr by 1,000 items (from 500 to 1,500 items) generated behaviour in the system similar to that seen with combination 4, in which the remanufacturing order was reduced by 1,000 items. For this reason, the system is sensitive to changes in the remanufacturing order size and specifically to changes due to the values assumed by the parameter Sr.

The second analysis involved simultaneous changes in both parameters Qm and sm from the respective values chosen for the base scenario. Table 4.3 shows the combinations of these parameters used in this analysis.

Table 4.3: Combinations of Qm and sm

Combination	Qm **(items)**	sm **(items)**
6	4000	300
7	5000	300
8	4000	200
9	3000	300
10	4000	400

Combination 6 used the values of the two parameters previously assumed for the basic scenario, while combinations 7 and 8 adopted an increase in the production order quantity through an increase in Qm and a decrease in sm, respectively. In combinations 9 and 10 the production order quantity is decreased through a reduction of Qm and an increase in sm respectively.

Changes in the parameter Qm affect the behaviour of the system particularly through changes in the value of the variables *Serviceable Inventory* and *production*, as Figure 4.27 shows. However, *Recoverable Inventory* and *remanufacturing* are less affected by changes in this parameter. Lower production order sizes decrease the average quantity of *Serviceable Inventory*, which leads to a reduction from 1,219 items for combination 7 to 886 items for combination 6 and 464 items for combination 9. Conversely, the average quantity of *Recoverable Inventory* is almost the same for the three combinations (around 2,000 items). Moreover, the trend of the three curves for the latter display almost the same mode of behaviour. The number of production reorders increases for lower production order sizes. Following the data, there are 15 reorders for combination 9 as opposed to 10 reorders for combination 7. The total stockout is higher in quantity (16,702 items) and frequency for the lower production order size (combination 9). This is followed by combination 7 with 12,463 items, and the basic scenario with 11,314 items.

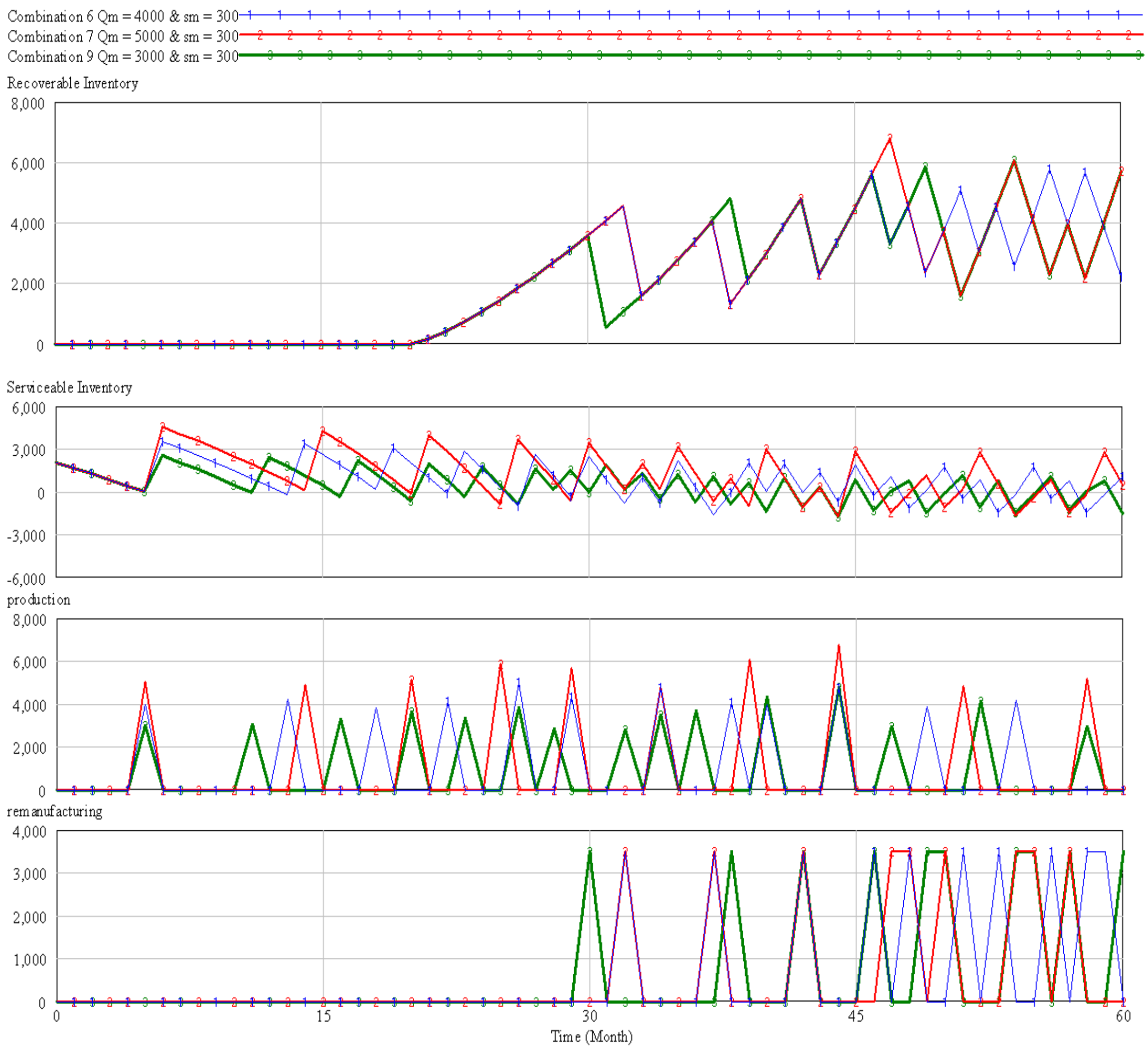


Figure 4.27: Effect of Qm

Also in this case, the system presents a lower sensitivity to the changes in the parameter sm as through the analysis of combination 8 and 10 the variables *Recoverable* and *Serviceable Inventory*, *production* and the stockout do not display significant changes in average and total quantity.

The last analysis was of the effect on the system of simultaneous changes in both the remanufacturing and production order. In particular, the analysis focused on the *Serviceable Inventory* which showed a higher sensitivity to the changes in both Sr and Qm. Figure 4.28 presents the results of this analysis. Specifically, the top of Figure 4.28 represents the first two cases in which both the remanufacturing and production order are decreased or increased by 1,000 items simultaneously. The bottom of the figure presents the last two cases in which the remanufacturing and production order are simultaneously increased or decreased respectively by 1,000 items.

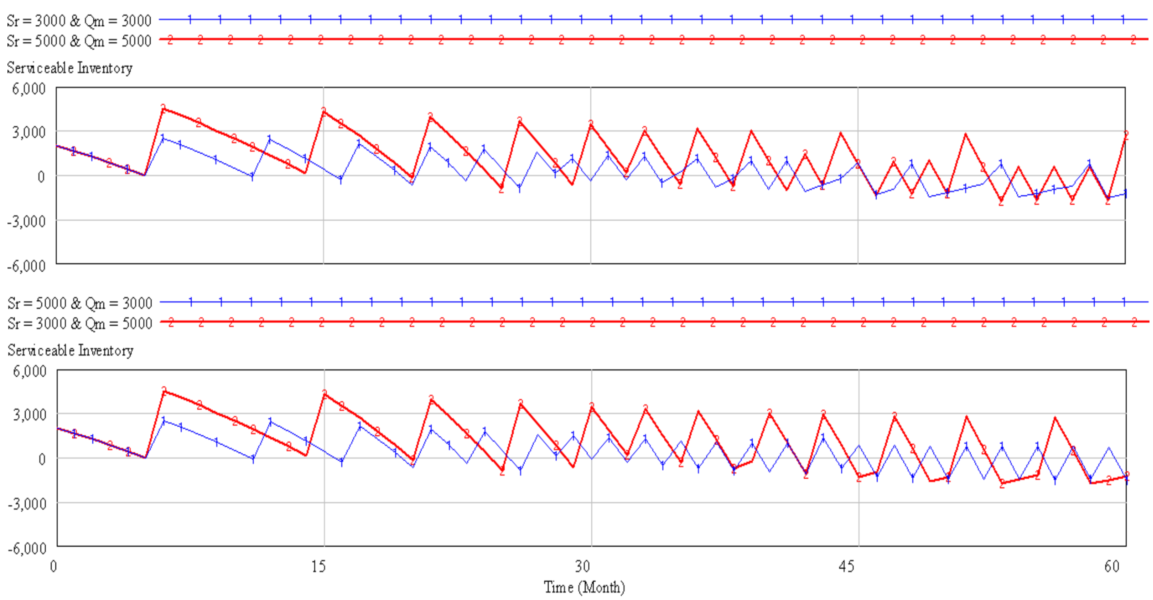


Figure 4.28: Effect of changes in remanufacturing and production order

The results for the first two cases reveal a decrease in the average quantity of *Serviceable Inventory* and an increase in the total quantity of stockout when both the remanufacturing and production order are decreased. The average quantity of the *Serviceable Inventory* drops from 1,231 items (Sr = 5,000 and Qm = 5,000) to 333 items (Sr = 3,000 and Qm = 3,000) while the stockout increases from 15,000 items to 20,543 items, respectively. This result highlights the issue within inventory systems related to a company's need to balance a reduced inventory level with an effective or responsive customer service in order to achieve a good level of competitiveness (Coyle, Bardi & Langley 2003; Fisher 1997). The target is to establish an efficient and responsive system where a lower inventory level reduces the inventory costs, such as holding costs, while at the same time offering a suitable level of customer service level that generates an appropriate cost of stockout. A company strategy that effectively facilitates this trade-off must incorporate higher rapidity and flexibility in both the company processes and the relationships among the actors involved in the supply chain. This leads to lower lead times and work in process inventory. The model proposed here does not consider such factors due to its generality in terms of the kind of product considered and the model's simplification of a real system. However, the previous analysis shows that the model is appropriate for considering this trade-off through analysis of the holding inventory and stockout costs.

The results of the last two cases reveal a higher sensitivity of the system to the production than remanufacturing order quantity. Even if the remanufacturing order is increased, the average quantity of *Serviceable Inventory* drops from 1,062 items (Sr = 3,000 and Qm = 5,000) to 516 items (Sr = 5,000 and Qm = 3,000) when the production order is reduced, while the stockout increases from 16,909 (Sr = 3,000 and Qm = 5,000) to 17,571 (Sr = 5,000 and Qm = 3,000) items. The lower effect of Sr on the average quantity of *Serviceable Inventory* and stockout is due to two main factors: the time and the quantity of recoverable returns. Firstly, the return process for possible returns generated by the sales at a particular time period t will start only after t + *RESIDENCE TIME*. This involves a delay in the remanufacturing compared to the production activity in fulfilling the orders for the *Serviceable Inventory*. This delay is included in the model through the basic scenario in which *Used Products*, *Collected Returns* and *Recoverable Inventory* were assumed to have an initial value equal to zero. However, when the remanufacturing process is running at full capacity and in parallel to production, it is constrained by the accumulated quantity of returns in the *Recoverable Inventory*, which represents the second main reason. The number of possible remanufacturing orders depends on the *Recoverable Inventory* level, which allows the realisation of a remanufacturing order only when the accumulation of recoverable returns reaches the level $Sr - sr$. This involves a greater use of production reorders than remanufacturing orders during the period of accumulation of recoverable returns. Time and quantity of recoverable returns are influenced by the *RESIDENCE TIME* and *returns rate fraction*, which are both affected by high levels of uncertainty. For these reasons, establishing a more precise *RESIDENCE TIME* and *returns rate fraction* can assist in setting an appropriate value for the remanufacturing (Sr, sr) and production (Qm, sm) order, in order to improve the efficiency and effectiveness of the production and inventory control process for remanufacturing.

4.3.3 Discussion

Based on the outcome of the validation analysis we determined that the developed model of the production and inventory system for remanufacturing is suitable for evaluating and investigating strategies aimed at improving the performance of the system through a simulation of scenarios. Specifically, through the direct structure validation we confirmed the capacity of the model equations to be logically and dimensionally consistent with the available knowledge of real-world scenarios. Through the sensitivity analysis, we also identified that the changes in the behaviour patterns of the model, due to particular assumptions regarding the changes in value for particular parameters, are consistent with a real system.

Another outcome of the sensitivity analysis was the identification of those parameters to which the model showed sensitivity. In particular, in line with the purpose of the model of evaluating and investigating strategies and focusing particularly on the returns process in order to improve the performance of the system, it was found that the model showed sensitivity to the changes or joint changes in the values of the main parameters involved in the returns process (*RESIDENCE TIME*, *SERVICE AGREEMENT WITH CUSTOMER* and *CUSTOMER BEHAVIOUR)*. Thus, these parameters can be used for the simulation analysis of scenarios in order to achieve the aims of the model.

4.4 Simulation of Scenarios for the Returns Process

The development of the model, and its validation, led to the final stage in the process of SD simulation modelling, which involved simulation of scenarios focusing on the main parameters of the returns process in order to reach conclusions, specifically to identify and evaluate the best policy and strategy to adopt and what occurs in the system if factors change or events intervene. In particular, the main purpose of the simulation is not predictions or forecasts of a future event, but rather to evaluate scenarios or alternative futures that may occur given certain assumptions or conditions (Morecroft 2007).

Before the various scenarios can be designed and simulated, we must first identify and present the measure of performance and the base scenario used for the simulation analysis. Then we discuss the various scenarios employed in the analysis and present the results of the simulations from which an evaluation can be undertaken of the best strategies to adopt to improve the performance of the system.

4.4.1 Performance Measure

The measure of performance for this simulation analysis represents the indicator whose changes in value under different scenarios and given certain values of the parameters enhance understanding of the conditions that might arise in the system. These conditions that represent the simulation results lead to an evaluation of strategies, which in turn provide guidelines as to how to improve the performance of the system.

As was found in the literature review, for most production and inventory systems for remanufacturing the objective is to minimise the average total inventory cost; therefore, the latter will be considered as a measure of performance for the simulation analysis. However, the analysis is not aimed at determining the optimal order quantity or reorder inventory level. Rather the objective is to identify the effects on the system of the main factors involved in the returns process, in particular residence time, service agreements offered by companies and customer behaviour. Changes in these factors are considered as events that intervene in a production and inventory system for remanufacturing where the returns process is characterised by uncertainty in the quantity and timing of returns.

The value of the total inventory cost for the analysis is obtained by adding a number of operational costs. These are the *set-up costs* for each production reorder and remanufacturing order, the *cost of stockout* for each out-of-stock sale, and the *holding costs* for recoverable and serviceable inventory. The choice of this particular sum of total cost in which the remanufacturing and production costs are excluded is based on several observations. Firstly, one of the assumptions previously mentioned in Section 4.2.1 determines that the model posits a disposal activity resulting from the inspection process rather than a planned disposal in recoverable inventory. This means that all accepted returns from the inspection are stored as recoverable inventory and used for the remanufacturing activity. Therefore, there are no inventory decisions that affect the remanufacturing and production activity in terms of quantity of items to be remanufactured and produced (van der Laan & Teunter 2006). Moreover, the mathematical formulation of the model considers the number of remanufacturing orders and production reorders rather than production and remanufacturing rates. These observations make the system independent of the remanufacturing and production activity, and consequently it excludes the production and remanufacturing costs. However, in order to potentially consider cheaper remanufacturing in place of production activity (remembering that the cost of remanufacturing is typically 40–60% of the cost of production (Mitra 2007)), different *set-up costs* are assumed for production reorder and remanufacturing orders. Moreover, this analysis focuses on the total inventory costs which exclude the collection and inspection/disposal costs.

The formulation of the total cost and operational costs using the simulation software is shown in Table 4.4. In this case, the values of the parameters are determined according to the theoretical basis drawn from the literature review.

Table 4.4: Formulation of the costs

set-up cost per remanufacturing order = 20 Units: $/order
set-up cost per production reorder = 50 Units: $/order
number of production reorder = IF THEN ELSE (production>0, production/production , 0) Units: order
number of remanufacturing order = IF THEN ELSE (remanufacturing>0, remanufacturing/remanufacturing, 0) Units: order
*Set-up costs = number of production reorders * set-up cost per production reorder + number of remanufacturing orders * set-up cost per remanufacturing order* Units: $
unit stockout cost = 10 Units: $/items

Table 4.4 – continued from previous page

*stockout costs = number of out-of-stock sales * unit stockout cost* Units: $
unit recoverable holding cost per time unit = 0.5 Units: $/items
*recoverable holding costs = Recoverable Inventory * unit recoverable holding cost per time unit* Units: $
unit serviceable holding cost per time unit = 0.8 Units: $/items
*serviceable holding costs = MAX (Serviceable Inventory, 0) * unit serviceable holding cost per time unit* Units: $
total cost = recoverable holding costs + serviceable holding costs + Set-up costs + stockout costs Units: $

The *set-up costs* are formulated as the sum product of the fixed set-up costs per reorder or order and the number of production reorders or remanufacturing orders, respectively. In this case only the fixed set-up cost is considered while variable set-up costs that involve activities such as transportation and materials handling are ignored. The *cost of stockout* is obtained through the multiplication of the unit cost for a lost sale by the number of lost sales. The latter are found through the negative values of *Serviceable Inventory* which represent unfilled demands and consequently lost sales. The recoverable and positive serviceable inventory on hand multiplied respectively by the recoverable and serviceable holding cost per item per time unit gives the inventory *holding costs*. The unit holding cost for serviceable inventory is considered greater than the unit holding cost for recoverable inventory as several storage-related factors such as insurance, taxes, deterioration, damage and capital invested can generate lower costs for the recoverable inventory.

4.4.2 Base Scenario

The base scenario represents and determines the values of the model parameters that we initially set in order to run the simulation of scenarios. Specifically, these scenarios are obtained by changing the value of the main parameters under study and at the same time keeping the other parameters at the value of the base scenario.

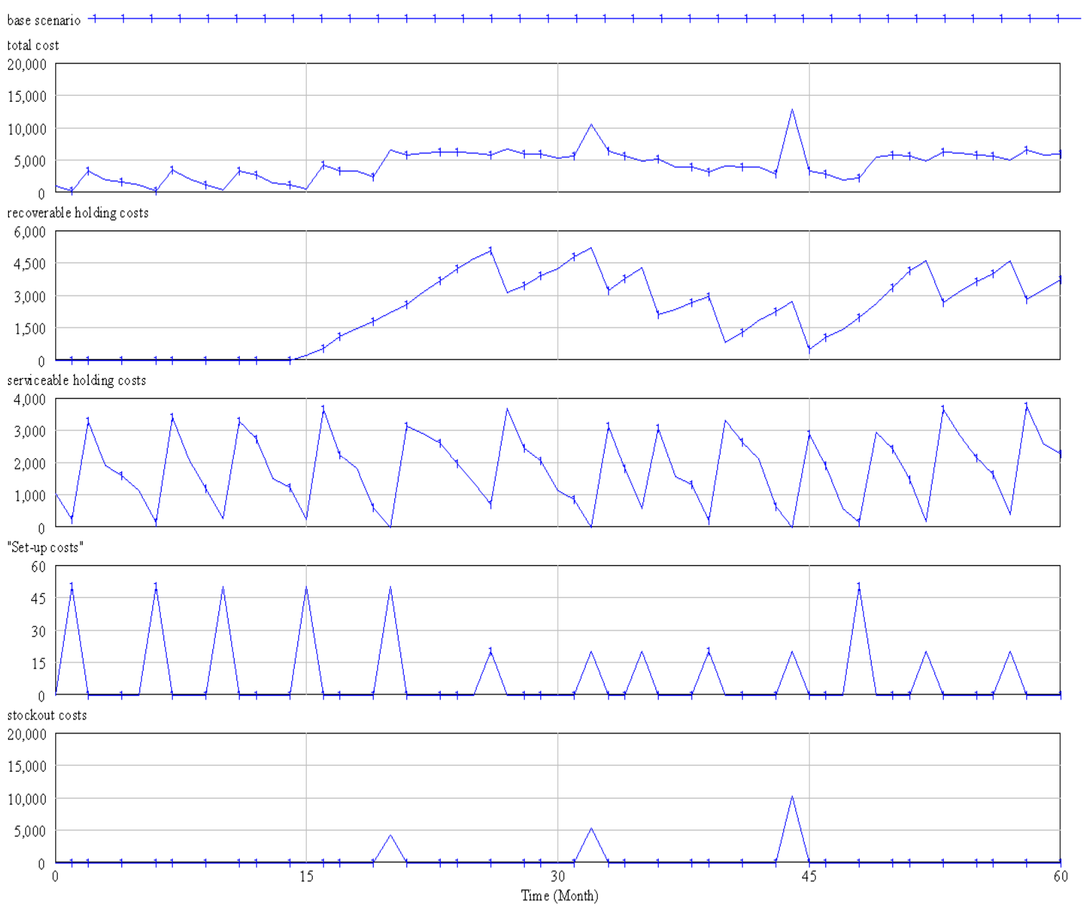


Figure 4.29: Costs trend for base scenario

The base scenario used for this simulation analysis includes the same values for the model parameters previously used for the sensitivity analysis outlined in Section 4.3.2. However, in this case, the assumed values for the product demand and residence time are changed in order to generalise the model for different kinds of products. Specifically, *demand* is set to a uniformly distributed random number. The random values are set at between 300 and 2,000 items with a fixed noise seed, in order to have the same sequence of random values for every simulation, which equals 2. The formulation of *demand* is thus represented as: *demand = RANDOM UNIFORM (300, 2,000, 2)*. Moreover, *RESIDENCE TIME* is set at 12 months. Figure 4.29 shows the costs trend for the base scenario during the planning horizon which is set at 60 months.

The evolution of the total cost shows a growing trend during the planning horizon. It is important to note that an increase in the total cost does not represent a negative aspect of the model. Indeed, company costs could increase due to reverse logistics activities such as remanufacturing and disposal, resulting in a subsequent need to optimise the total costs (Inderfurth 2005). However, our analysis does not examine the profit margin of the system but rather focuses on the effects that the returns process and several involved parameters have on the average total inventory cost. Under these considerations, it is possible to notice from Figure 4.29 a decreasing trend in the total cost for the time period between the months 30 ($5,342) and 45 ($3,370). This time period involves high remanufacturing activity as is shown by the reduction of recoverable inventory and the use of cheaper remanufacturing orders. Then, this high level of remanufacturing activity could be associated with the reduction of the total cost, as the serviceable holding costs have a constant or rather growing trend during the planning horizon, particularly for the same time period, and stockout costs have two peaks during the same period.

4.4.3 Scenarios Derived from the Returns Process

Our simulation of scenarios focused on the main parameters considered for the returns process. Thus, the scenarios were obtained through the combination of a range of values for those parameters related to the system policies defined for the returns process. Moreover, these parameters are those to which the model was sensitive during the sensitivity analysis. Specifically, the parameters are *RESIDENCE TIME* (RT), *SERVICE AGREEMENT WITH CUSTOMER* (SAWC) and *CUSTOMER BEHAVIOUR* (CB).

Table 4.5: Parameter values used for returns process scenarios

Scenarios	*RESIDENCE TIME* (months)	*SERVICE AGREEMENT WITH CUSTOMER*	*CUSTOMER BEHAVIOUR*
Base scenario	12	50%	2
Fast-used products	2	20%, 40%, 60%, 80%, 100%	1, 2, 3
	12	20%, 40%, 60%, 80%, 100%	1, 2, 3
	18	20%, 40%, 60%, 80%, 100%	1, 2, 3
Slow-used products	24	20%, 40%, 60%, 80%, 100%	1, 2, 3
	36	20%, 40%, 60%, 80%, 100%	1, 2, 3
	42	20%, 40%, 60%, 80%, 100%	1, 2, 3

The analysis focused on the effect of the three parameters on the average total inventory cost. Specifically, through this measure of performance changes in the behaviour of the modelled production and inventory system for remanufacturing were examined using 6 levels of *RESIDENCE TIME*, 5 levels of *SERVICE AGREEMENT WITH CUSTOMER* and 3 levels of *CUSTOMER BEHAVIOUR*. Table 4.5 lists the values of the parameters used for the analysis, which involved a total of 90 scenarios. The selection of the assumed values for the parameters corresponds as much as possible to a meaningful reflection of the real world for a broad range of products. However, following the purpose of this simulation analysis to evaluate strategies for improving the performance of the system, we believe that the exact value of the parameters is not as important as an understanding of the changes in the behaviour of the system under different scenarios.

The various scenarios are characterised by low and high *RESIDENCE TIMES*, which correspond with *fast-used products* and *slow-used products*, respectively. The choice of this table structure was based on the relationship between *RESIDENCE TIME* and type of product. *SERVICE AGREEMENT WITH CUSTOMER* is considered to be the policies/incentives that companies use to retrieve used products and *CUSTOMER BEHAVIOUR* the customer tendency to return them, respectively. The parameter values used to set the residence time are realistic as they can be associated with several remanufacturable products (Georgiadis, Vlachos & Tagaras 2006). The assumed values for *SERVICE AGREEMENT WITH CUSTOMER* can represent a broad range of company policies and incentive types which develop a relationship between companies and their customers in the returns process. In the same way, the different levels of *CUSTOMER BEHAVIOUR* are representative of a broad range of responsive attitudes.

Figure 4.30 presents the evolution of the average total inventory cost for various simultaneously simulated levels of *RESIDENCE TIME* and *SERVICE AGREEMENT WITH CUSTOMER*, given a *CUSTOMER BEHAVIOUR* level equal to 3. The numerical results are presented in Table 4.6.

Table 4.6: Average total inventory cost changing RT and SAWC

RESIDENCE TIME	**2**	**12**	**18**	**24**	**36**	**42**
SERVICE AGREEMENT WITH CUSTOMER						
20%	\$4683	\$4202	\$3950	\$3428	\$2986	\$2635
40%	\$4180	\$4466	\$3772	\$3607	\$3105	\$2717
60%	\$4048	\$3588	\$3638	\$3246	\$2848	\$2748
80%	\$4102	\$3632	\$3676	\$3276	\$2868	\$2762
100%	\$4124	\$3651	\$3454	\$3289	\$2877	\$2768

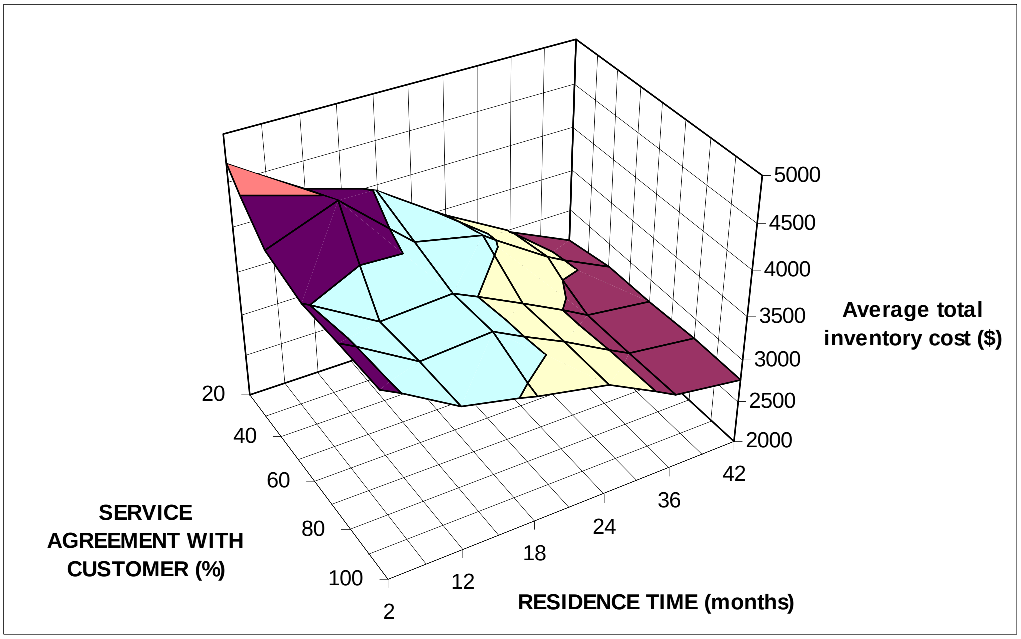


Figure 4.30: Evolution of average total inventory cost changing RT and SAWC

The first observation shows a decrease in the average total inventory cost for a high level of *RESIDENCE TIME*. This is due to the reduced cyclic nature of returns for *slow-used products*, which remain longer with the customers. In the model the reduced cyclic nature of return of a product is represented by the long time period between the product sale and its possible return. As is shown by *recoverable holding costs* in Figure 4.31, for a *RESIDENCE TIME* equal to 42 months, a portion of products sold at time 0 of the planning horizon become remanufacturable returns only after a long residence time, and during this residence time they do not affect the recoverable inventory and its associated cost. In a different way, products with short a resident time have a fast cyclic nature of return and are quickly involved in recoverable inventory and remanufacturing activity. Therefore, in the short time period, s*low-used products* have a reduced use of recoverable inventory and remanufacturing activity with a consequent reduction in the total inventory cost. It is also evident that *serviceable holding costs* are indifferent to the remanufacturing or production of the product and consequently of the residence time, and *stockout costs* are often special events, as Figure 4.31 shows.

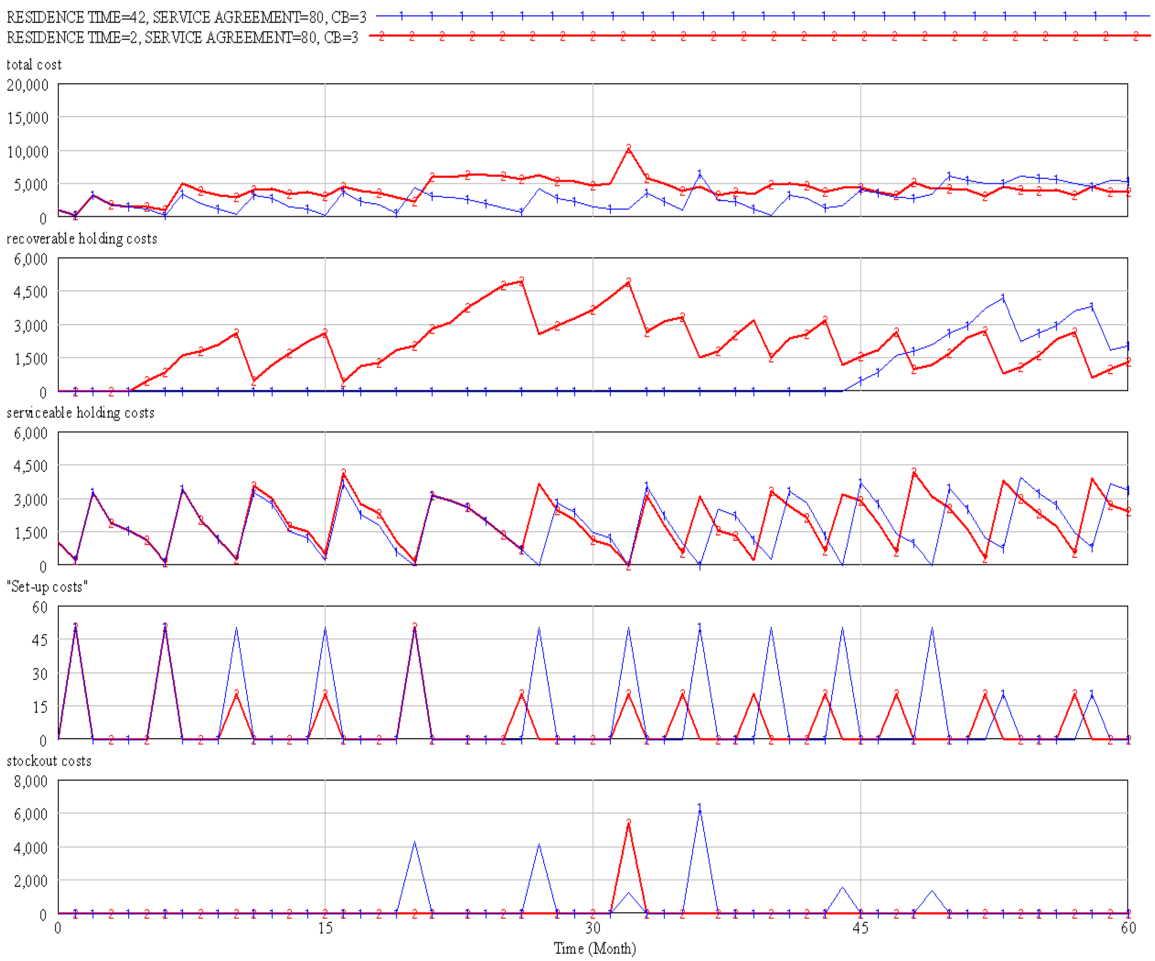


Figure 4.31: Evolution of operational costs changing RT

This observation does not prove that *slow-used products* are promising candidates for profitable remanufacturing systems. On the contrary, in the context of a closed loop supply chain, examples of profitable remanufacturing processes include f*ast-used products* such as single-use cameras (Kodak) and assemblies or sub-assemblies of copiers/printers (Fuji Xerox). These kinds of products generate high levels of return and recoverable inventory with a subsequent increase in the total inventory costs. At the same time, cheaper remanufacturing activity is a substitute for more expensive production activity, as is shown by the *set-up costs* in Figure 4.31. As the structure of the model does not involve remanufacturing and production costs then it is not possible to draw any conclusions regarding profitable remanufacturing. However, several examples are given of products with low residence times or short lifecycles and high returns rates for which high stock levels increase inventory costs. These products in the long run generate a more profitable remanufacturing activity due to reduced production costs such as purchasing and service costs (Flapper, Van Nunen & Van Wassenhove 2005).

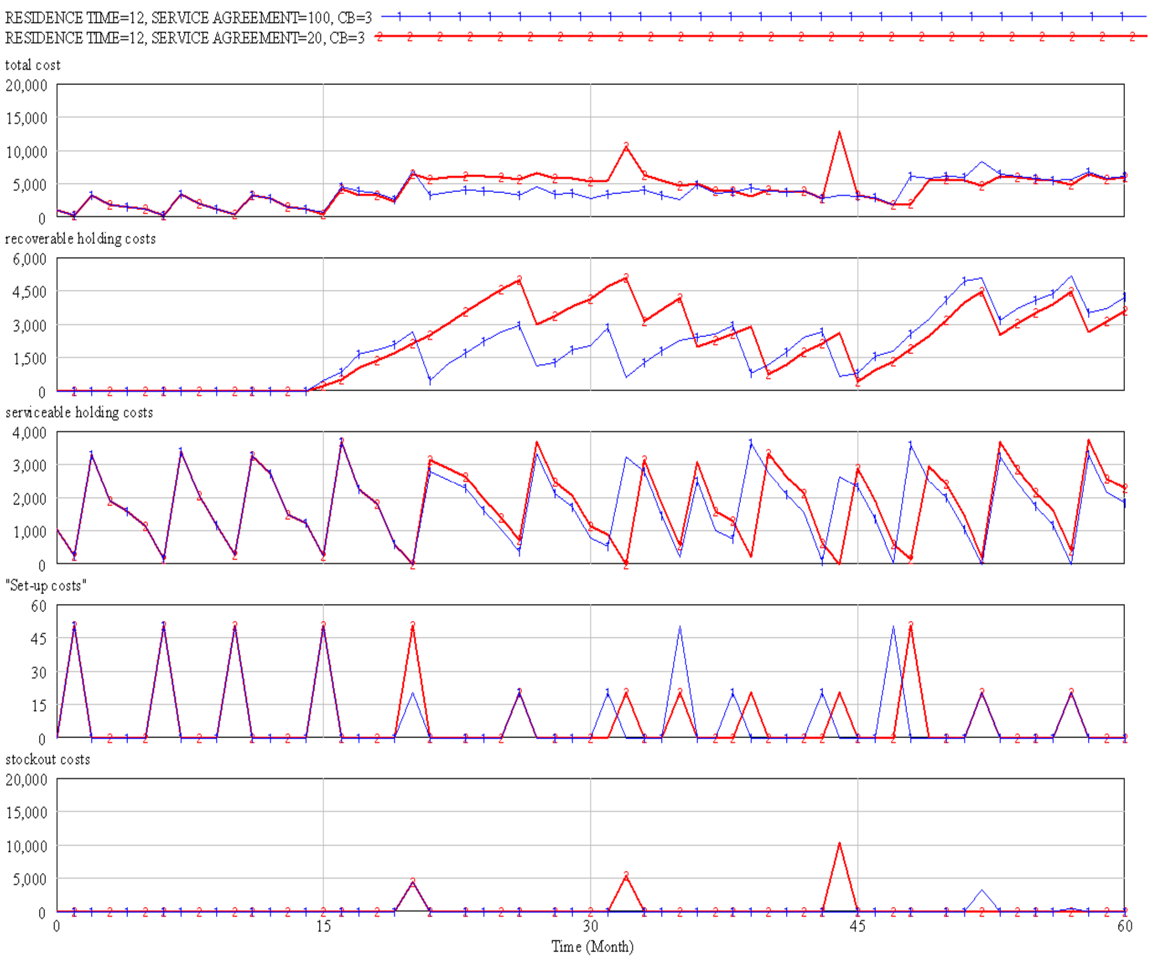


Figure 4.32: Evolution of operational costs changing SAWC

The second observation obtained through the scenarios simulation reinforces the possibility that a high returns rate can generate a profitable remanufacturability in closed loop supply chains. From Table 4.6 and Figure 4.30 it is possible to observe a decrease in the average total inventory cost for each level of *RESIDENCE TIME*, except for the highest one, by increasing the *SERVICE AGREEMENT WITH CUSTOMER* from 20% to 100%. The cost variation is not as significant as occurs by increasing the *RESIDENCE TIME*. However, it can improve efficiency in managing inventory in the remanufacturing process. High incentives for product recovery and consequently a high returns rate and quantity of remanufacturable returns can increase the level of recoverable inventory which can be used to generate remanufacturing orders faster as a substitute for production. This reduces the average level of recoverable inventory and consequently the average total inventory cost, as Figure 4.32 shows in relation to *recoverable holding costs*. Moreover, increasing remanufacturing activity does not negatively impact the effectiveness of the system, as is shown in Figure 4.32 where stockout quantity and costs are reduced for a higher returns rate.

Table 4.6 shows a higher reduction of the average total inventory cost, increasing the *SERVICE AGREEMENT WITH CUSTOMER* from 20% to 100%, for *fast-used products* than *slow-used products* for which an increase in cost characterises the highest residence time (42 months). This difference in cost trend is due to the lower influence of *slow-used products* on recoverable holding costs and recoverable inventory as noticed in the first observation. In this case, an increase in the service agreement or incentives increases the quantity of recoverable inventory but only after a long residence time. This surplus of recoverable inventory does not affect remanufacturing as a substitute for production activity in the short term. Therefore, an increase in service agreement for product recovery could have a lower or negative effect on average total inventory cost for *slow-used products* over a short time period. This is different for *fast-used products* where an increase in incentives affects the quantity of recoverable inventory in a shorter time period, which can then be used sooner in remanufacturing activity with subsequent benefits in recoverable inventory and production activity reduction. However, in the long term the return of *slow-used products* can be improved by a percentage increase in the service agreement. Increasing the planning horizon from 60 to 120 months, the average total inventory cost for *slow-used products* with a *RESIDENCE TIME* equal to 42 months decreases from $3,834 for 20% of *SERVICE AGREEMENT WITH CUSTOMER* to $3,601 for 100% of *SERVICE AGREEMENT WITH CUSTOMER*. Examples of closed loop supply chains for *slow-used products* such as white goods are presented in the literature (Flapper, Van Nunen & Van Wassenhove 2005). The main driver of the reverse logistic process for such products is government legislation, which stipulates the responsibility of producers to recover their end-of-life products. However, incentives to the customer and several other factors involved in the process are given in order to increase the returns rate for economic and environmental benefit.

Simulations, using the same values for the parameters *RESIDENCE TIME* and *SERVICE AGREEMENT WITH CUSTOMER* presented in Table 4.5, were undertaken by setting *CUSTOMER BEHAVIOUR* at equal to 2 and 1. Table 4.7 and Figure 4.33 show the evolution of the average total inventory cost for changes in *CUSTOMER BEHAVIOUR* and percentage of *SERVICE AGREEMENT WITH CUSTOMER*, with a *RESIDENCE TIME* equal to the base value of 12 months.

Table 4.7: Average total inventory cost changing SAWC and CB

CUSTOMER BEHAVIOUR	**CB3**	**CB2**	**CB1**
SERVICE AGREEMENT WITH CUSTOMER			
20%	$4202	$3534	$3339
40%	$4466	$4466	$3779
60%	$3588	$4391	$4230
80%	$3632	$4380	$4338
100%	$3651	$3651	$3651

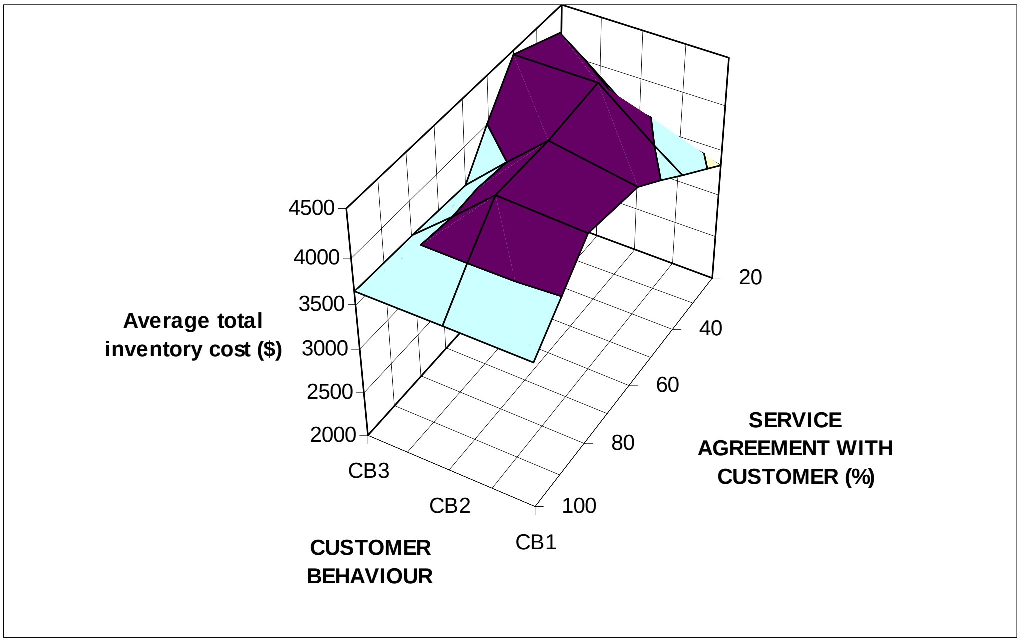


Figure 4.33: Evolution of average total inventory cost changing SAWC and CB

A reduction in the value of *CUSTOMER BEHAVIOUR* from 3 to 1 decreases the returns rate and consequently the average number of returns. This applies to every percentage value of *SERVICE AGREEMENT WITH CUSTOMER* except for 100%, for which the *return index* and consequently the returns rate is independent of customer behaviour. These simulation results correspond with and are thus representative of real-world scenarios, as a lower response from customers to company incentives for the recovery of used products in a closed loop supply chain system can reduce the quantity of returns. However, usually this does not occur for products for which companies maintain ownership such as products under leasing contracts, or for products that companies are responsible for recovering due to environmental government legislation.

This reduction in returns quantity resulting from changes in customer behaviour has several consequences on the system and its average total cost. From Table 4.7 and Figure 4.33 it is possible to observe that for higher percentages of *SERVICE AGREEMENT WITH CUSTOMER* such as 60% and 80% the average total inventory cost increases if the customer response (and returns rate) is lower. This is due to the lower level of recoverable returns in the short term. Higher levels of service agreement or incentives coupled with higher response levels from customers to these incentives increases the level of remanufacturable returns. Therefore, in a shorter period it is possible to use remanufacturing as a substitute for production activity with subsequent economic benefits from the reduction of recoverable inventory and holding costs and the cheaper manufacturing processes. This observation is confirmed by the *recoverable holding costs* shown in Figure 4.34.

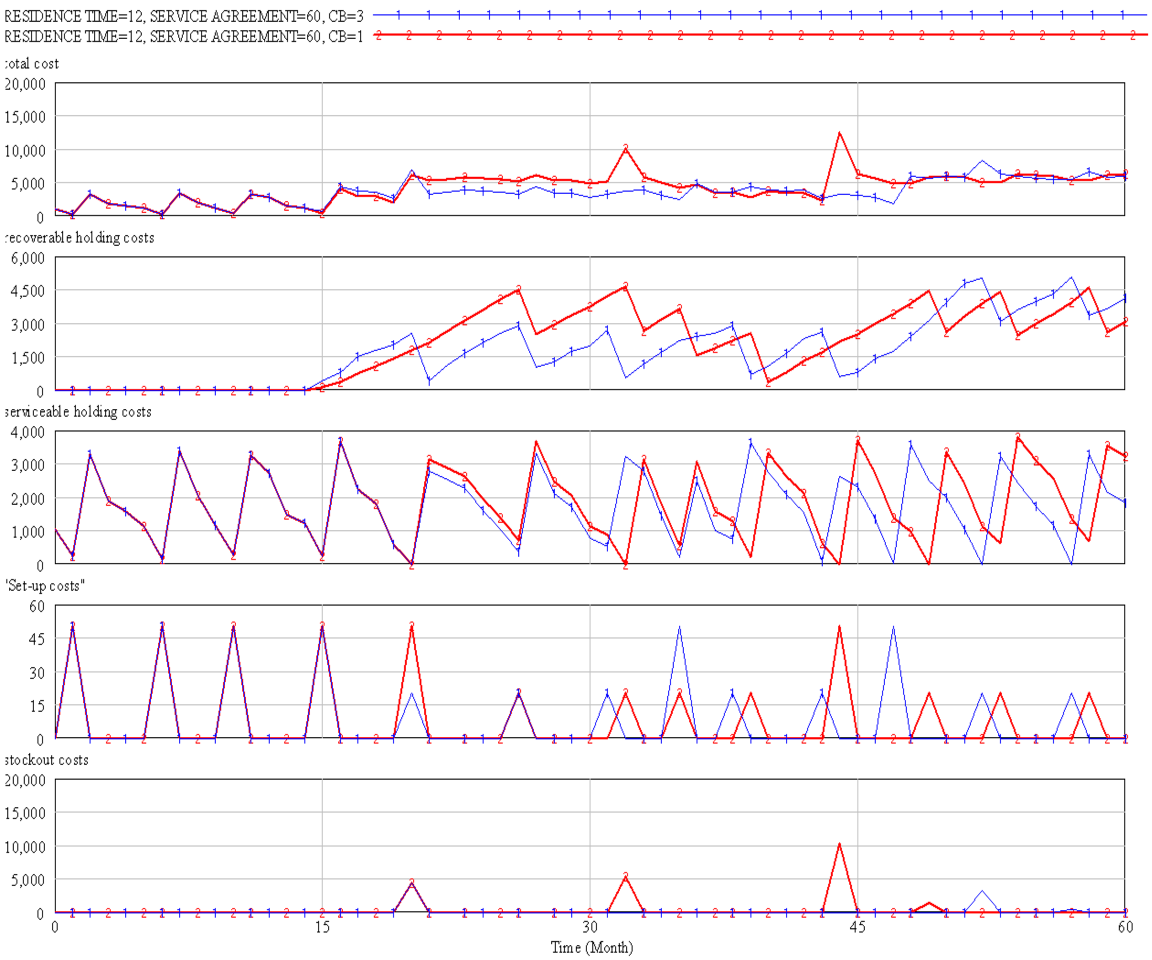


Figure 4.34: Evolution of operational costs changing CB

From Figure 4.34 it is possible to observe that when the remanufacturable returns start to accumulate, the *recoverable holding costs* are higher for the higher value of *CUSTOMER BEHAVIOUR* due to the greater quantity of recoverable inventory. However, the latter allows for a prompt remanufacturing activity, which in turn reduces the recoverable inventory level and the costs. The same observation has been previously noted for Figure 4.32 with an increase in *SERVICE AGREEMENT WITH CUSTOMER*.

From Table 4.7 and Figure 4.33 it is evident that for lower percentages of *SERVICE AGREEMENT WITH CUSTOMER*, such as 20% and 40%, the average total inventory cost decreases if the *CUSTOMER BEHAVIOUR* value decreases. In this case, as the top of Figure 4.35 shows, the low quantity of returns due to low incentives and low customer response leads to a low level of recoverable inventory, which is almost always lower than the level of recoverable inventory for higher values of *CUSTOMER BEHAVIOUR*. The latter involves more remanufacturing activity but not enough to reduce the recoverable inventory level. Therefore, in the case of low values for *CUSTOMER BEHAVIOUR* the level of recoverable inventory involves lower holding costs but at the same time lower remanufacturing activity. This scenario could negatively affect companies involved in remanufacturing activity for closed loop supply chain systems which require a sufficient quantity of returns to increase remanufacturing as a substitute for production activity. However, the bottom of Figure 4.35 and the data in the right column of Table 4.7 indicate that in the case of low *CUSTOMER BEHAVIOUR* the increased percentage in the service agreement might not generate an expected reduction in cost. As already mentioned, this is due to insufficient remanufacturing activity needed to reduce and lower recoverable holding costs.

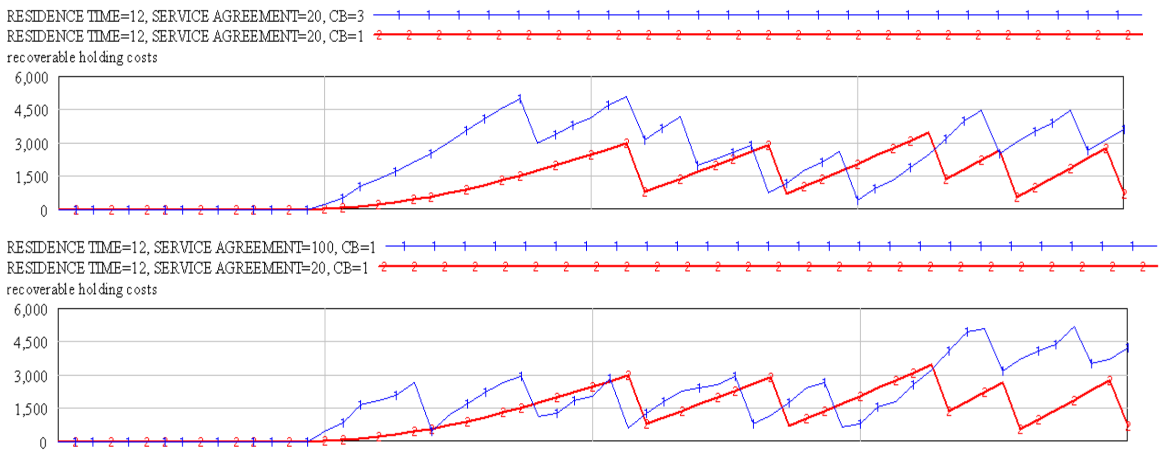


Figure 4.35: Evolution of *recoverable holding costs* changing CB and SAWC

4.4.4 Evaluation of Strategies

Remanufacturing activity in closed loop supply chain systems requires an adequate quantity of remanufacturable returns in order to establish a manufacturing process where cheaper remanufacturing can be used as a substitute for production activity. This process leads to economic and environmental benefits in reducing the reliance on the more costly production activity. Remanufacturing uses 85% less energy than production, and reduces landfill, pollution and raw material usage (Gray & Charter 2007). Moreover, the simulation analysis revealed that an increase in remanufacturing activity can optimise the inventory system and its costs through enhanced efficiency in the management of recoverable inventory. *Slow-used products* with a longer residence time present in the short term a reduced use of recoverable inventory due to their lower cyclic nature of return and consequently lower inventory cost compared to *fast-used products*. However, in the short term this could negatively affect remanufacturing as a substitute for production activity due to a shortage of remanufacturable returns. On the other hand, *fast-used products* can be used within a shorter time period and therefore prompt remanufacturing activity which reduces the inventory cost through greater efficiency in recoverable inventory management. A prompt remanufacturing activity depends on the recoverable inventory on hand which, as the simulation analysis showed, is also influenced by *SERVICE AGREEMENT WITH CUSTOMER* and *CUSTOMER BEHAVIOUR*. An increase in both these parameters leads to a higher returns rate, which in turn generates a higher level of recoverable inventory on hand and consequently increases the possibility of prompt remanufacturing activity. For these reasons, the evaluation suggests that, for companies involved in remanufacturing activity as a substitute for the more expensive production activity, a shorter residence time combined with an increased level of service agreement or incentives for product recovery and a higher response from customers to these incentives can generate economic benefits through an increase in the quantity of remanufacturable returns.

However, uncertainty in returns flow, particularly related to timing and quantity of returns, could influence the results of the previous analysis of the inventory system. Some companies manage this uncertainty in the quantity of remanufacturable returns stored in the recoverable inventory without attempting to balance returns with demands, preferring instead to dispose of excess inventories on a periodic basis (Guide 2000). In the same way, several authors use a planned disposal of recoverable inventory in their models and posit a simple probabilistic returns quantity or define all demands as returns (van der Laan, Dekker & Salomon 1996; van der Laan & Salomon 1997; Vlachos, Georgiadis & Iakovou 2007). In our model, planned disposal of recoverable inventory is not considered, which could add a new inventory cost and be more profitable, following the reverse logistics *preponement* concept (Blackburn et al. 2004), during or prior to the inspection stage. However, uncertainty in timing and quantity of returns is specifically tackled in this study through the use of parameters such as *RESIDENCE TIME*, *SERVICE AGREEMENT WITH CUSTOMER* and *CUSTOMER BEHAVIOUR*. Analysis of their relationships in the returns process can provide a forecasted returns rate and a possible time of return for used products with different product characteristics and in different industries. Knowledge of a product's residence time coupled with combinations of incentives in product recovery such as trade-in and leasing contracts can also assist in estimating the time and quantity of returns. Moreover, incentives, particularly leasing contracts and changes in product design for easier disassembly and recovery of product/components, can result in a reduction of the residence time, and subsequent benefits as those previously mentioned in connection to *fast-used products*. For example, the introduction of leasing contracts, or changes in product design that enable customers to easily disassemble and return used products/components, can help to fix or reduce the residence time. Through such incentives, companies can influence customer behaviour in returning used products. By adopting policies such as deposit fees, free collection or repurchase of used products, fees paid upon the return of used products, and improving product design, as well as clear information/advertising about reverse logistics activities and environmental responsibilities can assist in enhancing customer behaviour in relation to the returns process.

4.5 Case Studies

In this section we assess the robustness of the research findings obtained through the simulation, which leads to the evaluation of the strategies aimed at improving the performance of the system. For this purpose, we use the data and information collected from the two companies employed as case studies: the Australian Mobile Telecommunications Association (AMTA) and Fuji Xerox Australia. These companies are involved respectively in reverse logistics and remanufacturing activity, and in particular are engaged in returns process activities, which meant they were appropriate case studies for our research.

The research findings were obtained from a generic model of the production and inventory system for remanufacturing. For this reason, the assessment involves a comparison between the research findings and the data and information collected from these companies in order to find similarities and to verify the former by referring to the actual real-world practices of these companies. Specifically, the quantitative data and information collected from AMTA are employed first. Then the similarities between the

AMTA data and both the qualitative data and the information collected from Fuji Xerox Australia are identified and discussed.

4.5.1 MobileMuster

In order to assess the research findings revealing that an increase in the service agreement or incentives for product recovery, which in turn increases the customer behaviour towards the returns process, then leads to a higher returns rate, the first Australian company case is used.

MobileMuster is the official national recycling program of the mobile phone industry in Australia (KPMG 2008). It is supported by AMTA, which is the national body of the mobile telecommunications industry. The program is a free recycling project for mobile phone users, which avoids landfill activity and recovers material from used mobile phones, entailing environmental and economical benefits. Project managers were contacted in order to obtain data and information, not about the recycling program (which is not directly relevant to this study), but the influence of incentives on customers to return used products, customer behaviour and returns rates. Data and information were obtained from the annual report for 2007–2008 of the organisation (KPMG 2008).

According to the report, the company has developed numerous incentives and service agreements with customers, retailers and other reverse logistics actors such as local councils and recyclers in order to increase returns/collection rates and improve customer behaviour in relation to the returns process. In particular, the focus is on free used product collection from customers. This has been achieved by distributing reply paid recycling satchels available in selected mobile phone packs and by setting up public collection points nationwide in retailers and Australia Post outlets. Other incentives include customer communications and environmental campaigns about the MobileMuster program published in catalogues, on websites, through direct marketing and television advertising presented by mobile manufacturers, service centres and retailers. These activities have achieved varying results. In particular, Table 4.8 shows the evolution of particular KPIs for the MobileMuster program for the years 2005 to 2008. It is interesting to notice that since 2005 awareness of the recycling program, which represents consumer behaviour in relation to the reverse logistics program, has increased from 46% to 75% and at the same time collection and collection rates have increased. The latter two factors are representative of the quantity of returns and the returns rate of used mobile phones.

Therefore, similar to our findings, these company incentives have enhanced customer behaviour towards the returns process, which in turn has led to an increased returns rate.

Table 4.8: Evolution of KPIs for the MobileMuster program

Key Performance Indicators (KPIs)	2007/08	2006/07	2005/06
Mobile Phone Collection (tonnes)	**97**	**78**	**42**
Annual Collection Rate	**18.9%**	**18%**	**15%**
Disposal to Landfill Rate	**4%**	**5%**	**9%**
Awareness of Mobile Phone Recycling (Consumer Behaviour)	**75%**	**69%**	**46%**

4.5.2 Fuji Xerox Australia

The case study of Fuji Xerox Australia is presented in this section in order to assess two of the research findings obtained through the simulation analysis. The first regards our belief that benefits can be obtained in remanufacturing activity through the combination of a shorter residence time and an increased level of service agreement or incentives for product recovery. The second regards the significant influence of service agreement or incentives for product recovery on the uncertainty in quantity and timing of returns.

The case study employs qualitative data and information from this world leader in remanufacturing processes, obtained through interviews with company management and drawn from the existing literature. Specifically, the interviews were conducted at the Eco Manufacturing Centre located in Sydney.

The Eco Manufacturing Centre is the distribution centre for remanufactured printer and copier assemblies or sub-assemblies, which would otherwise be landfill for the Asia-Pacific Region (Fuji Xerox Australia Pty Limited 2007b). Assemblies and sub-assemblies, removed from equipment during maintenance service calls, are remanufactured at this centre. According to the managers, the Eco Manufacturing Centre focuses on and deals only with remanufacturing activity. For this reason, returns are an essential element in its remanufacturing activity, and predicting the quantity and timing of returns is essential to ensuring an efficient inventory and planning/scheduling for remanufacturing.

The information obtained from the managers is used to assess the first research finding. Specifically, the introduction of changes in product design as an incentive for product recovery through the easier disassembly and recovery of components rather than the whole machine, which in turn leads to faster recovery of returns or shorter residence times, was strongly supported by the Fuji Xerox managers. Indeed, new machines are built for easier and faster disassembly, recovery and remanufacturing process. In this way, remanufacturing activity can focus on modules with shorter residence times and easier remanufacturability. The company's aim is to increase remanufacturable returns and obtain profitable remanufacturing activity as a substitute for production activity. The work of the Eco Manufacturing Centre, which deals only with remanufacturing activity, supports this aim.

In terms of the second research finding, Fuji Xerox managers believe that a *full service agreement with customer* is an important strategy in the remanufacturing process. Fuji

Xerox draws up a full service and maintenance agreement with its customers whose response is usually to lease the products. The full service agreement has a number of targets, including a marketing strategy to increase service levels for the customer. However, from the remanufacturing activity point of view the full service agreement is also a returns process strategy to increase control of the quantity and timing of returns as well as to improve remanufacturing activity. The service is conducted by engineering teams, who provide service and repairs for breakdowns or when customers find the product is not working satisfactorily, as well as preventive maintenance of products. Using diagnostic tools, this maintenance service investigates the reasons for failure and opportunities to extend the product life (Fuji Xerox 2007). This process involves two main analyses:

- Failure Mode Analysis: to identify the reasons for failure of failed assemblies and sub-assemblies.
- Signature Analysis: to determine the remaining life of the assemblies and sub-assemblies through an examination of their critical performance parameters.

Data collection on these processes has led to continuous improvement of the basic product design and has resulted in a number of improvements. Durability of main assemblies and sub-assemblies, which are usually measured based on a possible maximum number of copies to be completed, is designed so as to enable replacement of all of the components at the same time. In this way, during preventive maintenance it is possible to predict when it will be necessary to replace the assemblies to improve product performance and when it will be necessary to replace them altogether. This process is guided by computer systems that identify whether or not there is a remanufacturing program for an assembly. During the breakdown and preventive maintenance, assemblies and sub-assemblies are replaced, and information on problems, solutions and forecasts for future replacement is provided. If the replacement is not possible at the maintenance stage because there is no prompt availability of new assemblies, an order to the local warehouse is made. Used assemblies and sub-assemblies are collected by the service engineers, valet service staff or dealers to be returned and stored at the local warehouse. From the local warehouses, they are transported to the Eco Manufacturing Centre to be re-engineered and remanufactured to again possess the quality of new products. Finally, they are packaged and stored in the surrounding warehouse as new products, waiting to be transported to the central distribution centre of Fuji Xerox Australia.

From the information collected we can conclude that one of the reasons why the Fuji Xerox managers at the Eco Manufacturing Centre strongly support the introduction of a full service and maintenance agreement with customers is to increase control of the quantity and timing of returns. Indeed, the use of leasing contracts for products, combined with a service agreement that can generate a forecast regarding the quantity and timing of returns, allows the company to keep track of the quantity and location of equipment and have a degree of control over the returns rate.

4.6 Summary

In this chapter, we developed the first generic SD simulation model of the production and inventory system for remanufacturing within the context of closed loop supply chains. We focused, particularly for the simulation analysis, on the returns process of the system in which the returns rate was modelled using relationships between particular factors that affect the system. The selected factors identify the time period for which products stay with customers, or residence time, and the quantity of possible returns based on customer demand or the return index. In particular, the return index was obtained by considering the relationship between the company incentives or service agreement with the customer aimed at encouraging used products recovery, and the customer behaviour in returning them. The remanufacturing process was also modelled and a pull inventory control policy was applied within the process.

The modelling process followed the main steps of the SD approach. The qualitative modelling involved the development of the CLD and description of the main feedback loops. The quantitative modelling involved the development of the SFD and related mathematical formulations. The model was then validated using extreme condition tests for a direct structure validation, and a sensitivity analysis for a structure-oriented behaviour validation. After the validation, simulation of scenarios was performed in order to evaluate strategies aimed at the improvement of the performance of the system. In particular, the simulation analysis was undertaken using various levels of the three major parameters that affect the returns process: residence time, service agreement with customer and customer behaviour.

By analysing the total inventory cost as a measure of performance of the system, several findings were obtained regarding the effects of residence time and changes in the level of company incentives and the resulting customer behaviour. The main finding is that companies engaged in remanufacturing activity can enhance their efficiency in managing inventory through shorter residence times and an increased level of company incentives, which results in improved customer behaviour. This leads to a higher level of recoverable inventory on hand and consequently the possibility of prompt remanufacturing as a substitute for production activity, which in turn reduces the recoverable inventory level and its related holding cost.

Moreover, company incentives for the recovery of used products have significant influences on the uncertainty in quantity and timing of returns and ultimately on total inventory costs. Increasing company incentives or service agreements with customers, which in turn increases customer behaviour in returning used products, can improve the control of returns. Two company case studies (the Australian Mobile Telecommunications Association through the MobileMuster program and Fuji Xerox Australia) were employed to assess the research findings. In particular, Fuji Xerox Australia offers incentives such as changes in product characteristics, full service and maintenance agreements with customers, and leasing contracts in order to reduce the residence time and improve their control over returns.

Chapter 5

MODELLING THE REMANUFACTURING PROCESS

5.1 Introduction

In this chapter a generic SD simulation model of the production and inventory system for remanufacturing is developed in order to explore the dynamics of the remanufacturing process. The objective is to evaluate strategies for improving the performance of the system, focusing on particular factors that affect the process. Specifically, the analysis will focus on the effects of capacity planning and lead times on the system, based on push and pull inventory policies.

The development of the SD simulation model involves a relaxation of some of the assumptions previously outlined in Section 3.2, and the reasons for doing so are provided further on. The process steps of SD simulation modelling used for this model are similar to those presented in Chapter 4. However, in this case different variables and their interrelationships, as well as different feedback loops and mathematical equations affecting and representing the dynamic behaviour of the system, are adopted. Therefore, a detailed description of the qualitative and quantitative modelling process and of the validation methods applied is provided. In line with the objective of the modelling previously outlined, a simulation of scenarios focusing particularly on the remanufacturing process is generated. The robustness of the simulation findings and of the model is assessed by practical implication on the basis of information and data collected on a company (CEVA Logistics) related to similar activities within the modelled remanufacturing process.

5.2 Model Building

The model building for the production and inventory system for remanufacturing focusing on the remanufacturing process required a relaxation of some of the assumptions previously considered for the model developed in Chapter 4. This was based on our need to analyse the effects of particular activities and factors involved in the remanufacturing process on the system. However, the introduction of these activities and factors involved changes in the structure of the model and in particular for the structure of the Causal Loop Diagram (CLD) which in turn involved changes to the Stock and Flow Diagram (SFD) and related mathematical formulations.

A discussion of the relaxed assumptions and the reasons for relaxing them is provided first. Then we present and describe the CLD and SFD developed to represent the system.

5.2.1 Remanufacturing Process and Assumptions

The model of the remanufacturing process focuses on several activities within the production and inventory system for remanufacturing. These are included in Figure 5.1, which shows how the returns process between *Demand* and *Returns* is excluded from the analysis. Several assumptions applied to the system in Chapter 4 are now relaxed in order to remodel and reformulate the remanufacturing process. In particular, remanufacturing and production capacity is no longer considered infinite, and backorders and lead times are introduced into the system.

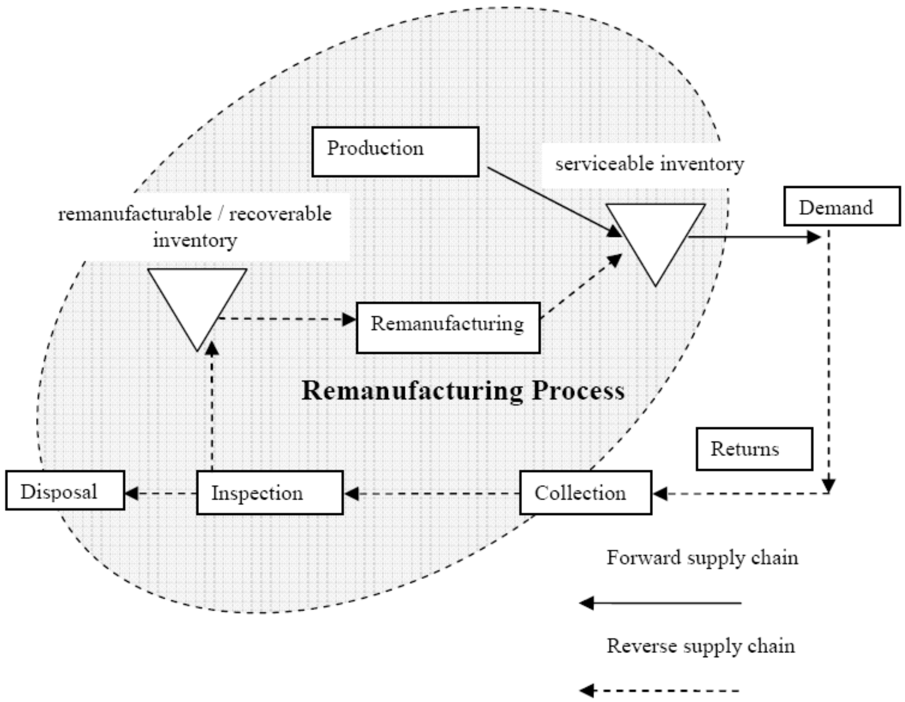


Figure 5.1: The remanufacturing process

The efficiency of the production and inventory system for remanufacturing obtained through the planning and control of several activities such as production, remanufacturing and optimal inventory order quantities can be affected by limited system capacity. Moreover, the latter has to be shared between the remanufacturing and production activity. For this reason, capacity planning can be a further strategy for companies involved in the remanufacturing process to adopt. From a survey of 320 firms actively engaged in remanufacturing processes in the US, one half of them reported using dynamic lot size techniques based on capacity constraints for resource planning, scheduling and inventory control (Guide 2000). Moreover, traditional techniques commonly used for capacity planning in manufacturing activity, such as the *Bill of*

Resources approach, the *Overall Factors* approach and the *Resource Profiles* approach, can be used in remanufacturing also (Guide, Srivastava & Spencer 1997).

The model presented in this chapter does not involve particular capacity planning techniques as they are not the main subject of interest in this study and could increase the complexity of the model. However, as the integration between the remanufacturing and production activity into the same system can limit the joint capacity usage (Kleber 2006), the latter is introduced as a system variable. The objective is to analyse the shared capacity between remanufacturing and production for this integrated system whose target is to increase the use of cheaper remanufacturing as substitute for the more expensive production activity.

Besides capacity planning, companies involved in the remanufacturing process must plan a number of strategic and operational activities, and this includes the importance of planning lead times in the production and inventory system (Tang, Grubbström & Zanoni 2007). A planned lead time is one of the greatest tools identified by remanufacturing companies who are under constant pressure to reduce lead times in order to remain competitive (Guide 2000). For these reasons, we considered it appropriate to introduce remanufacturing and production lead times into the model.

Finally, we determined that the use of stockout, which was applied to the model in Chapter 4, is not suitable for a remanufacturing process. The stockout approach assumes that customer orders not immediately filled become lost sales or negative values in the serviceable inventory. However, we believe that such a practice should imply the use of backorder in order to avoid negative values in the serviceable inventory. Most manufacturing firms are not able to immediately satisfy customer orders, so they are then maintained as a backlog of unfilled orders and accumulated as the difference between total orders and actual sales (Sterman 2000). For these reasons, backorder activity is introduced into the model where unfilled orders are maintained in backlogs.

5.2.2 Qualitative Modelling

The introduction into the system of remanufacturing and production capacity, lead times and backorder required the definition of new system variables in order to model and develop the CLD. Moreover, the structure of the CLD was changed to consider more suitable system policies for the remanufacturing process and to make appropriate use of standard system dynamics formulations.

The production and inventory system for remanufacturing requires an explicit backorder activity, specifically during the stage at which customer orders are satisfied through the serviceable inventory. The introduction of the backorder policy into the system leads to a distinct use of the two variables *sales* and *demand*. The former represents the actual fulfilled orders delivered to the customers, while *demand* is an exogenous variable defined by different time series patterns which represents customer demand from which actual orders are generated. These orders can be accumulated in backorder as well as used to define a desirable serviceable inventory, which in turn is characterised by a certain level of inventory coverage. The latter reflects company policy and represents the time period during which the desired serviceable inventory covers customer demands.

In this system inspection activity, as seen for the model developed in Chapter 4, selects the collected returns as either accepted for remanufacture or rejected for disposal. However, in contrast to the model developed in Chapter 4, in this new model the policy of storing as recoverable inventory only the required quantity of accepted returns is applied. In this way, the system can generate efficiency in the recoverable inventory as well as in the inspection activity for which only the necessary quantity of collected returns are inspected and accepted to be stored as remanufacturable items. In order to model such a policy the variables *expected accepted returns* and *gap current recoverable* are introduced into the system. The former represents the expected quantity of accepted returns at the inspection stage, considering the average percentage of disposal, while the latter is the difference between an *upper recoverable inventory stock level* and the actual recoverable inventory level. The *upper recoverable inventory stock level* is defined by the remanufacturing capacity and represents the recoverable stock level at which a remanufacturing order can be issued.

Remanufacturing and production activity are characterised mainly by their respective capacities and lead times. Specifically, remanufacturing capacity and production capacity affect their respective order quantities. The latter in turn is influenced by another system variable, *gap serviceable inventory*, which represents the difference between the desired and the actual serviceable inventory level. A full list of the variables involved in this system modelling is presented in Table A.2 of Appendix A, including the type and unit characteristic for each. However, a full description of the system variables is presented in this section.

The CLD representing the system, with a focus on the remanufacturing process, is presented in Figure 5.2. The diagram shows all the influence relationships among the variables listed in Table 5.1 and the feedback structure of the system. However, the feedback loops involved are not represented in Figure 5.2 because of the limited space in the diagram. These will be represented in a clearer way further in the chapter.

In the diagram, customer *demand* for products, which generates customer *orders* which in turn generate *returns* from *sales*, represents the input for the remanufacturing process. Customer orders are satisfied either by the new produced items or by the as-good-as-new remanufactured items which replenish the serviceable inventory. Differently from the model presented in Chapter 4, the returns process is modelled through a simple influence relationship between *sales* and *returns*.

The model presents 14 feedback loops that involve several activities such as inspection, remanufacturing, production, inventory control, sales and backorder. Specifically, 4 positive feedback loops (R1, R2, R3 and R4) and 10 negative feedback loops (B1, B2, B3, B4, B5, B6, B7, B8, B9 and B10) are presented in the diagram.

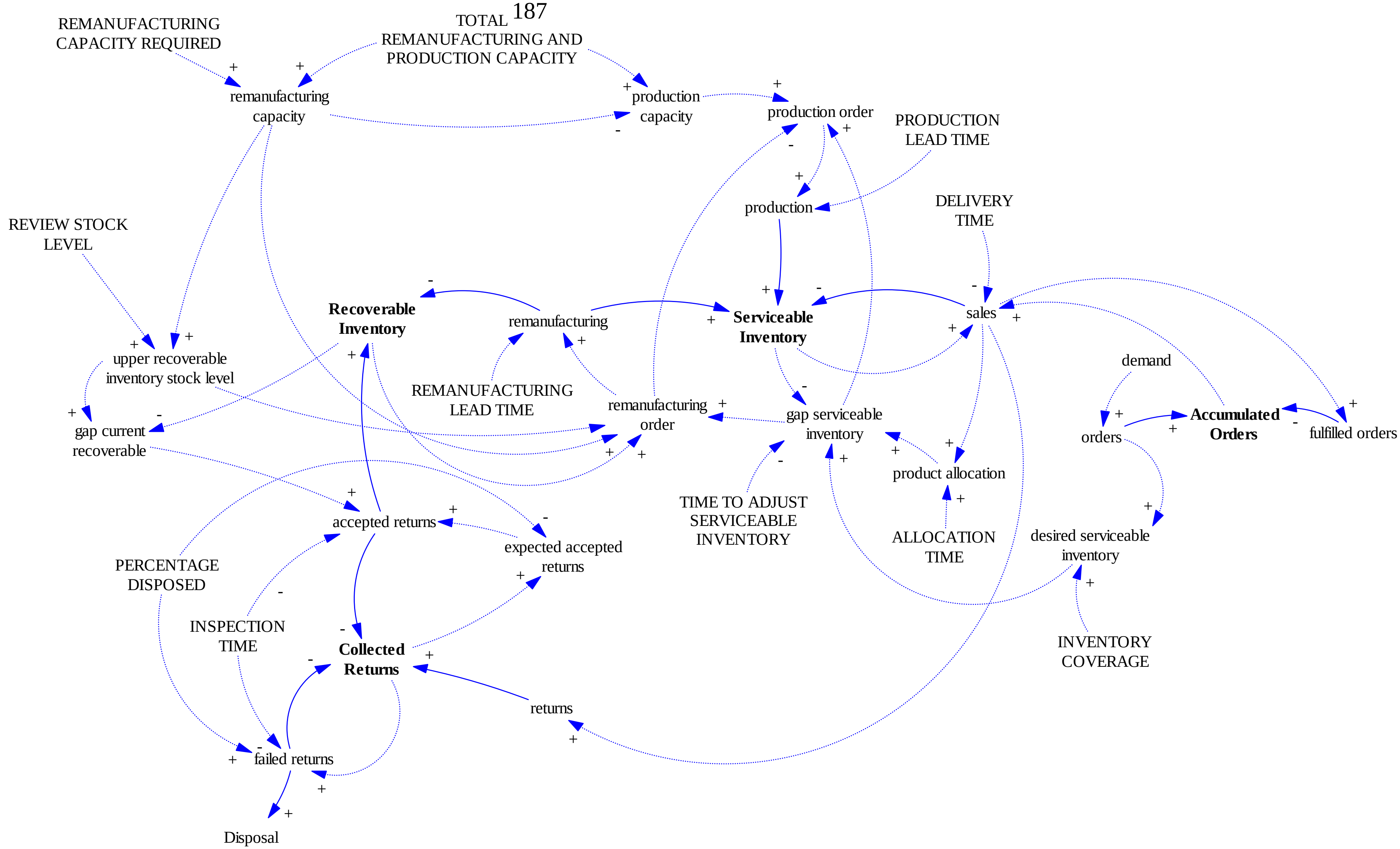


Figure 5.2: CLD for the remanufacturing process

The feedback loops shown in Figure 5.3 represent remanufacturing activity. The positive loop R1 generates a growth in the value of the variables involved into the process and consequently an amplification of the remanufacturing activity. Differently, the two negative loops B7 and B8 bring the remanufacturing activity towards a desired value through recoverable and serviceable inventory control, respectively.

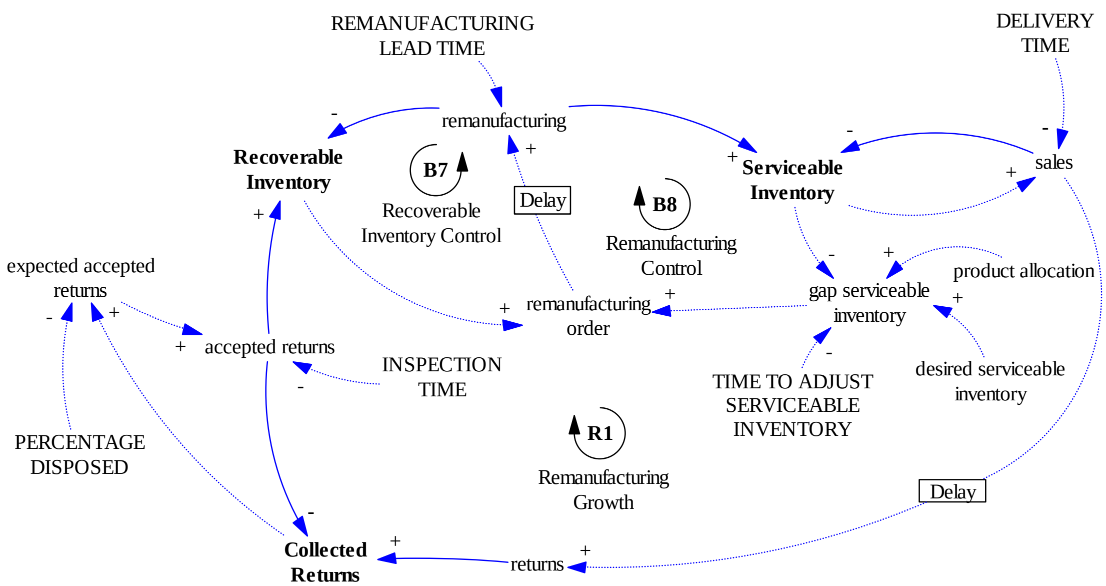


Figure 5.3: Remanufacturing feedback loops in the remanufacturing process

The *returns* obtained from the *sales*, after the period of time for which the products are used by the customers, generates the physical flow of items. The latter are collected as *Collected Returns* then inspected and, if accepted for remanufacturing, stored as *Recoverable Inventory*. Later, the recovered items are used in *remanufacturing* to produce as-good-as-new products, which are stored, after the remanufacturing lead time, as *Serviceable Inventory*, which in turn is used to feed into *sales*.

The inspection activity, which generates the *accepted returns* to be used in remanufacturing, is influenced by the variable *expected accepted returns*. The latter represents a forecast of collected returns which will be accepted for remanufacturing.

This possible quantity of items depends on the value of *PERCENTAGE DISPOSED* which was already defined in the analysis of the returns process in Chapter 4. However, as the CLD shows, the quantity of actual accepted returns could not have the same value as the *expected accepted returns* since the variable *accepted returns* is also influenced by the current level of recoverable inventory.

Remanufacturing activity is influenced by the variable *remanufacturing order*. This represents the required quantity of recoverable items to be remanufactured in order to obtain a certain quantity of as-good-as-new products to be stored as serviceable inventory. For this reason, *remanufacturing order* is influenced both by the current recoverable inventory level (*Recoverable Inventory*) and by the quantity of products required by the serviceable inventory in order to satisfy *sales*. This required quantity of products is represented by the variable *gap serviceable inventory* which in turn is influenced by the *desired serviceable inventory* level, the current *Serviceable Inventory* level and the *product allocation*. The desired serviceable inventory level is set in order to cover the actual customer orders, while the products allocation defines the serviceable items allocated to sales (Figure 5.2). Remanufacturing starts when a required remanufacturing order is issued. However, the remanufactured quantity will be available only after a period of time represented by the *REMANUFACTURING LEAD TIME*.

The positive loop R1 involves the variables: *returns*, *Collected Returns*, *expected accepted returns*, *accepted returns*, *Recoverable Inventory*, *remanufacturing order*, *remanufacturing*, *Serviceable Inventory* and *sales*. If this feedback loop dominates the system behaviour, remanufacturing activity and the value of each variable involved in the loop would grow exponentially during the process. For example, an increase in the quantity of *sales*, which in turn increases the quantity of *returns*, would increase the quantity of collected, inspected and accepted items and consequently the quantity of items stored as recoverable inventory. The larger the recoverable inventory, the bigger the possible remanufacturing orders, amplifying the remanufacturing activity and thus the quantity stored as serviceable inventory, which in turn again increases *sales*. The negative loops B7 and B8 prevent an unrealistic or infinite growth of recoverable inventory and remanufacturing activity, respectively. Specifically, B7 generates inventory control through a negative relationship between *remanufacturing* and *Recoverable Inventory* that generates a reduction in the recoverable inventory and consequently in the remanufacturing orders if remanufacturing increases. The negative loop B8 generates a control on remanufacturing activity through changes in the serviceable inventory level. Specifically, the negative relationship between *Serviceable Inventory* and *gap serviceable inventory* leads to a decrease in the required quantity of new products (*gap serviceable inventory*) if the serviceable inventory level increases. This generates a reduction in the number of remanufacturing orders, which in turn reduces the remanufacturing activity. In this way, the negative loop B8 also models a possible pull inventory policy for serviceable inventory for which the system reacts to customer orders by producing only a required quantity of products (Coyle, Bardi & Langley 2003). However, detailed explanations about the pull and push policy used for the serviceable inventory through the value of the variable *INVENTORY COVERAGE* will be provided later.

Therefore, the positive feedback loop R1 reinforces changes in the variables involved and generates remanufacturing growth, which would shift the system far from the usual balance between the inventory levels and the remanufactured quantity. For this reason, the two negative loops are used to limit the effects of R1 and to return the system towards a desired balance.

The production and inventory system for remanufacturing thus requires integration between remanufacturing and production activity. The latter, as Figure 5.4 shows, is influenced by the variable *production order* which represents the required quantity of items to be produced and stored as serviceable inventory. This flow of produced items joins the flow of as-good-as-new items generated by the remanufacturing activity to satisfy the *sales*. However, the produced quantity will be available only after a period of time represented by the *PRODUCTION LEAD TIME*.

Figure 5.4 shows the negative loop B4 which introduces production activity into the system. The variables involved are: *returns*, *Collected Returns*, *expected accepted returns*, *accepted returns*, *Recoverable Inventory*, *remanufacturing order*, *production order*, *production*, *Serviceable Inventory* and *sales*. The positive loop R1 generates continuous growth of the remanufacturing activity, which in turn increases the value of the *Serviceable Inventory*. The latter in turn is increased by the positive physical flow originated by *production*. However, the negative loop B4 limits the effects of the positive loop R1 through the reduction production activity that is not required. This reduction is achieved through the negative relationship between *remanufacturing order* and *production order*. Specifically, an increase in remanufacturing orders decreases the production orders, which in turn reduces production activity and the flow of produced items towards the *Serviceable Inventory*.

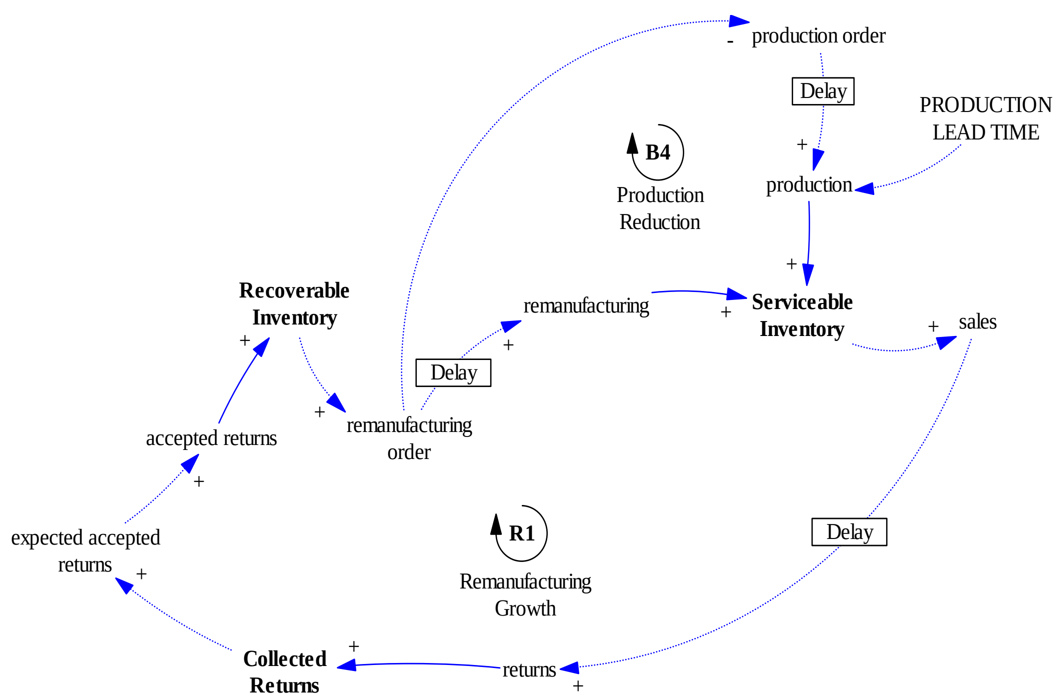


Figure 5.4: Production reduction feedback loop

Developed in this way, the negative loop B4 defines and implements the remanufacturing process policy to use the more costly production activity only when the cheaper remanufacturing activity cannot satisfy the entire demand for new items due to a shortage in recoverable inventory.

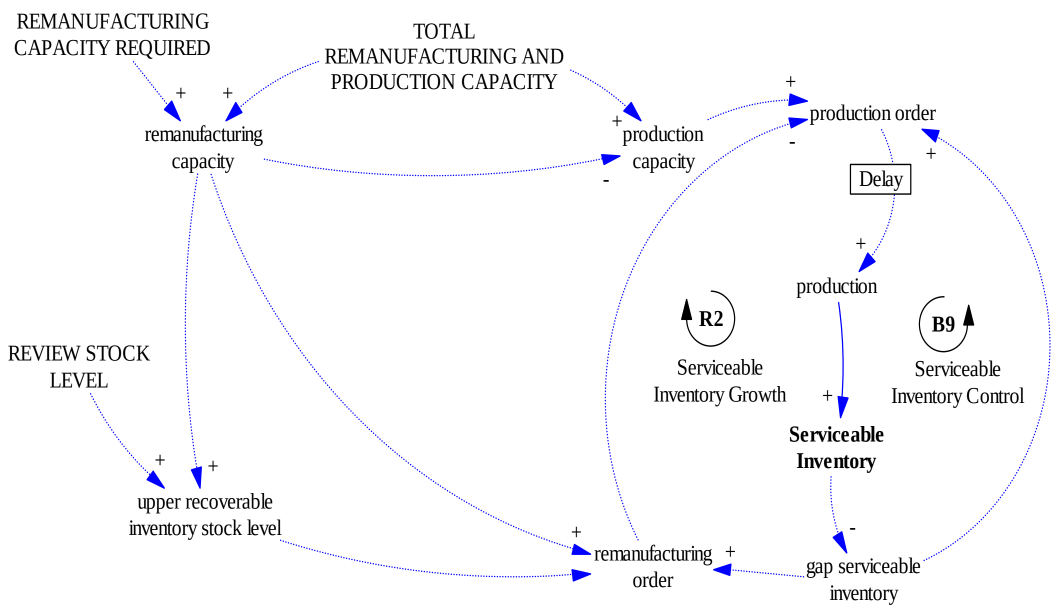


Figure 5.5: Serviceable inventory growth and control feedback loops

Production activity is involved in another two feedback loops: the positive R2 and the negative B9. Figure 5.5 shows these two loops as well as the influence relationships among remanufacturing orders, production orders and system capacity. The total capacity of the system in generating new products for the *Serviceable Inventory* is represented by the exogenous variable *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY*. The latter must be shared between remanufacturing and production activity in order to have a definite *remanufacturing* and *production capacity*. These two variables positively affect the quantity of items to be remanufactured (*remanufacturing order*) and produced (*production order*), respectively. Moreover, remanufacturing activity is also influenced by another variable: *upper recoverable inventory stock level*. This represents the required minimum level or quantity on hand of recoverable inventory at which a remanufacturing order can be issued. Specifically, if the serviceable inventory requires new products to satisfy sales and at the same time the recoverable inventory level has reached the value of *upper recoverable inventory stock level* (similar to the concept of the ($Sr - sr$) level presented in Figure 4.6), then, and only then, can a remanufacturing order be issued. In this way, the relationship between *upper recoverable inventory stock level* and *remanufacturing order* defines a pull inventory policy for the recoverable inventory. This policy ensures that recovered items (*Recoverable Inventory*) are not pushed towards the remanufacturing process as soon as an amount of items becomes available (van der Laan & Salomon 1997). Rather, they are remanufactured only when they reach and eventually stay at a definite quantity level (*upper recoverable inventory stock level*) and if serviceable inventory requires new products. In this way, the recovered items are held in the cheaper recoverable inventory and, through the remanufacturing process, only the required quantity of as-good-as-new products is stored in the more expensive serviceable inventory.

Figure 5.4 presents the control activity for the value of the variable *Serviceable Inventory* through the combined effects of the positive loop R1 and the negative B4, which generate a balance between the remanufactured and the produced products flow. However, the product flows generated for the *Serviceable Inventory* are also controlled by the variable *gap serviceable inventory*, which positively influences *remanufacturing order* and *production order*, as Figure 5.5 shows. In particular, the relationship between *gap serviceable inventory* and *remanufacturing order* creates an insidious positive loop R2 which can generate an unwanted exponential growth of production activity and consequently of the serviceable inventory. For example, a decrease in the required quantity of new products (*gap serviceable inventory*) generates a decrease in remanufacturing orders and remanufacturing activity, which in turn increases production orders and production activity. This increased flow of newly produced items then generates an increase in the value of *Serviceable Inventory*, which in turn decreases again the value of *gap serviceable inventory*. However, the negative loop B9 prevents such exponential growth through a positive relationship between *gap serviceable inventory* and *production order*. In this way, a decrease in the former generates at the same time a decrease in the latter, bringing the system under production and serviceable inventory control.

The behaviour of the inspection activity in the system is defined by three negative feedback loops, shown in Figure 5.6. The negative loop B1, similar to the model in Chapter 4, defines a balance between the level of *Collected Returns* and the quantity of items that failed the quality test (*failed returns*).

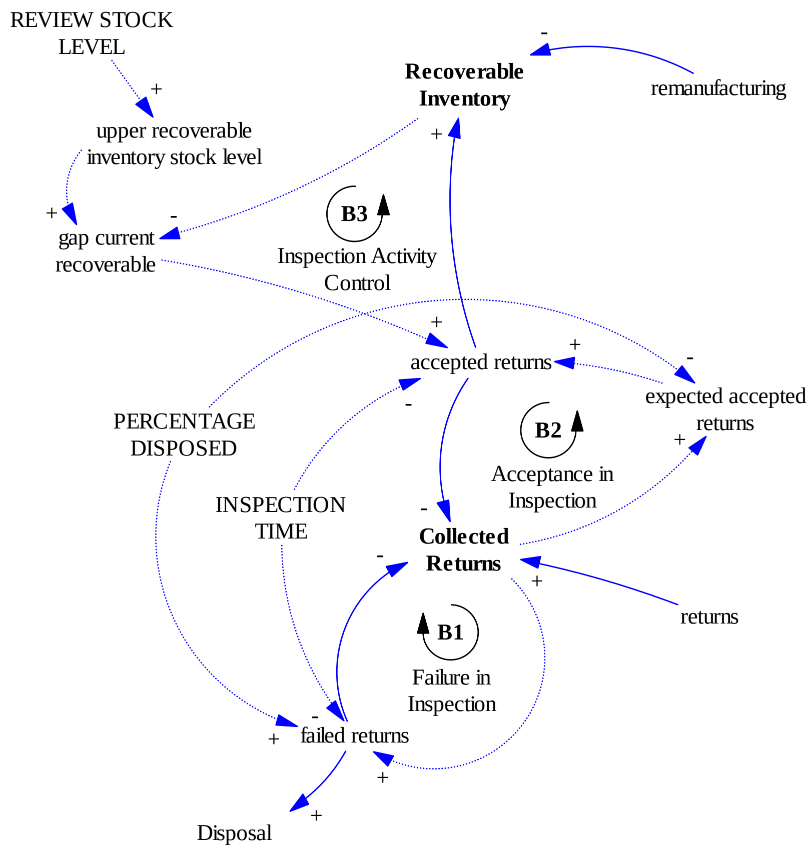


Figure 5.6: Inspection feedback loops

For this model, the negative loops B2 and B3 are based on the influence relationships that the variable *accepted returns* has with the two factors *expected accepted returns* and *gap current recoverable*. The latter represents the required quantity of items needed for the *Recoverable Inventory* to reach the *upper recoverable inventory stock level* and to issue a possible remanufacturing order. In other words, when the recoverable inventory on hand is lower than the *upper recoverable inventory stock level*, a required quantity of items (*gap current recoverable*) is generated as an order to be fulfilled through inspection activity which then provides accepted items for remanufacture (*accepted returns*).

The negative loop B2 prevents an exponential growth of the accepted items during the quality test due to the effects of the positive loop R1 (Figure 5.4). As Figure 5.6 shows, an increase in *returns* increases the level of *Collected Returns*, which in turn increases the quantity of *expected accepted returns* through the fixed value of *PERCENTAGE DISPOSED*. Since an increase in *expected accepted returns* causes an increase in the quantity of *accepted returns* and in turn causes a decrease in *Collected Returns*, the negative loop B2 is created. An increase in the quantity of *accepted returns* increases also the level of *Recoverable Inventory*, which in turn decreases the *gap current recoverable*. Since a decrease in *gap current recoverable* causes a decrease in the flow of accepted items to be stored as recoverable inventory, the negative loop B3 is created.

The negative loop B3 generates a control in the physical flow of the inspected and accepted returns towards the recoverable inventory and defines the inspection activity policy used within the system. Several authors have assumed a planned disposal of recoverable inventory in their models (van der Laan, Dekker & Salomon 1996; van der Laan & Salomon 1997; Vlachos, Georgiadis & Iakovou 2007). This means that the flow of accepted returns increases the quantity of items in the recoverable inventory in an uncontrolled manner and planned disposal occurs for every item that exceeds a fixed level (disposal level). In contrast, in this model, where planned disposal of recoverable inventory is not considered, the physical flow of accepted returns is controlled by the discrepancy between the desired level of recoverable inventory (*upper recoverable* *inventory stock level*) and the current recoverable inventory on hand (*Recoverable Inventory*). This discrepancy is represented by the variable *gap current recoverable*, which controls the flow of accepted returns towards the recoverable inventory by allowing only the required quantity of items through. In this way, the cost of planned disposal in the recoverable inventory is avoided, as a planned inspection activity policy holds returns at the collection stage and inspects and accepts only the right quantity of items required by the recoverable inventory.

Often companies are unable to immediately fulfil orders generated by customer demand. In particular, this occurs for companies involved in a pull-based supply chain for which several activities such as procurement, production and distribution are driven by actual customer orders rather than the forecast demand. For this reason, backorder is used to capture unfulfilled orders and to respond to actual customer orders through a desired serviceable inventory level.

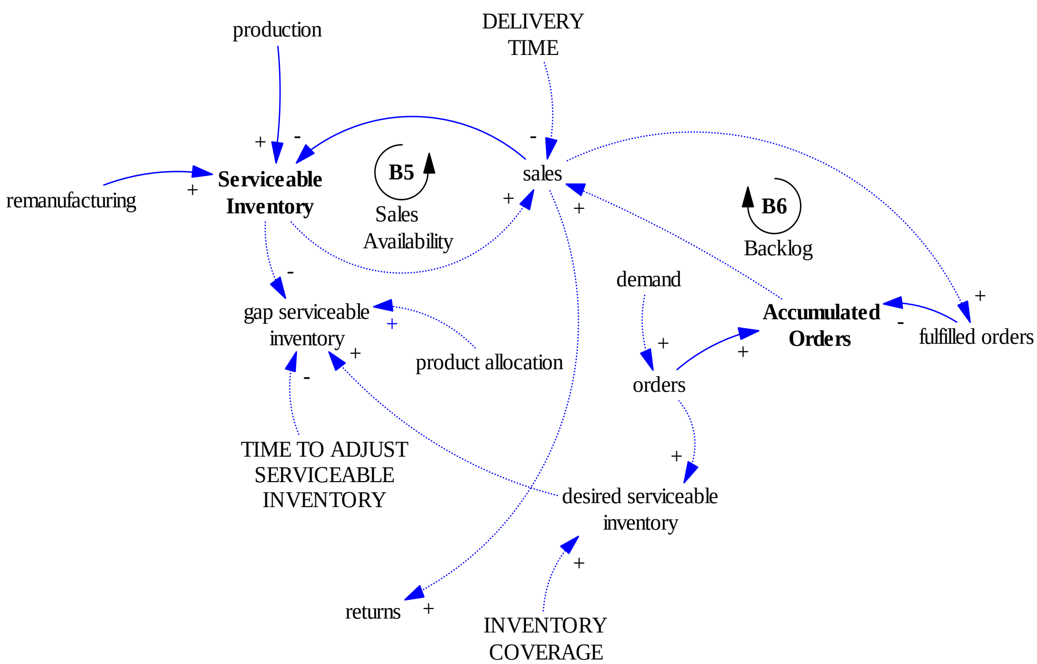


Figure 5.7: Sales and backorder feedback loops

Figure 5.7 shows the two negative feedback loops involved in sales and backorder. Loop B6 represents a backlog of unfulfilled customer orders, which increases the difference between orders and actual sales (Sterman 2000) which represent the quantity of available final products shipped to the customers. *Orders* generated by customer *demand* are accumulated in *Accumulated Orders*. This physical flow of items causes an increase in the *Accumulated Orders* level, which in turn increases the quantity of *sales*. Since an increase in *sales* causes an increase in the quantity of *fulfilled orders*, which in turn decreases the *Accumulated Orders*, the negative loop B6 is generated.

In the model, customer orders differ from customer demands in order to distinguish between possible orders (*demand*) and confirmed orders (*orders*) which can represent a percentage of customer demands. For this reason, the desired inventory of final products (*desired serviceable inventory*) is set considering the actual *orders* and not the *demand* in order to represent a system that is closer to a pull-based supply chain. Figure 5.7 shows another factor that influences the value of the desired inventory of final products—*INVENTORY COVERAGE* (Morecroft 2007). This factor represents the number of days, weeks or months over which a company plans to accumulate a certain desired level of inventory to cover the expected customer demand for that same period. The chosen value of inventory coverage in the model defines the use of a pull or push strategy for the serviceable inventory. For example, an increase in *INVENTORY COVERAGE* causes an increase in the *desired serviceable inventory* level, which in turn increases the value of the variable *gap serviceable inventory*. An increase in the latter, as the CLD shows (Figure 5.2), generates an increase in remanufacturing and production activity, which in turn increases the *Serviceable Inventory* level. This higher inventory level is not generated following actual customer orders but rather in response to the planned inventory coverage. This makes the system less responsive to customer demand and closer to a push inventory system entailing reduced backorder costs as the orders are filled immediately yet higher serviceable inventory costs. In a different way, a value for *INVENTORY COVERAGE* that leads the *desired serviceable inventory* level to equal the actual customer *orders* causes changes in the value of *gap serviceable inventory* and consequently in the *Serviceable Inventory* level within the system which, in this case, is more responsive to the customer demand. This leads the remanufacturing and production activity to be orders driven with consequent lower inventory levels and higher backorders as the orders are not filled immediately. In this scenario, the system is closer to a pull inventory control.

The negative loop B5 simply defines a balance between *Serviceable Inventory* level and *sales*. Such a balance avoids any exponential growth of the sold products resulting from continuous growth of the serviceable inventory due to the physical flows of remanufactured and produced items.

The allocation of products is required in the system in order to create a planning and control mechanism for order processing. Without an allocation of products the system could generate lower remanufacturing and production orders since the allocated serviceable inventory for sales could be seen as available serviceable inventory on hand. This in turn can generate, for example, an increase in the backorders quantity due to an inaccurate analysis of the behaviour patterns of the system. Specifically, if the *gap serviceable inventory* was affected only by the *desired serviceable inventory* (orders) and the *Serviceable Inventory* on hand, it could generate remanufacturing and production orders without considering that a quantity of the serviceable inventory is generated by previous orders and allocated for sales. For this reason a *product allocation*, which is related to the *sales*, is used in the system in order to ensure the *gap serviceable inventory* is influenced by the net and available *Serviceable Inventory* on hand.

The use of the variable *product allocation* in the model generates three feedbacks loops, as Figure 5.8 shows. The positive loop R3, which involves the variables *sales*, *product allocation*, *gap serviceable inventory*, *remanufacturing order*, *remanufacturing* and *Serviceable Inventory*, can generate an exponential growth of remanufacturing activity. For example, an increase in customer orders, which in turn increases the *desired serviceable inventory* and consequently the *gap serviceable inventory*, generates a growth of remanufacturing activity. The latter in turn generates a growth in the *Serviceable Inventory* level, *sales* and *product allocation*, which in turn again increases the *gap serviceable inventory*. However, the relationships between the *Serviceable Inventory* and the *gap serviceable inventory* and between the former and *sales* which generate the negative loops B5 (Figure 5.7) and B8 (Figure 5.3) prevent the effect of loop R3.

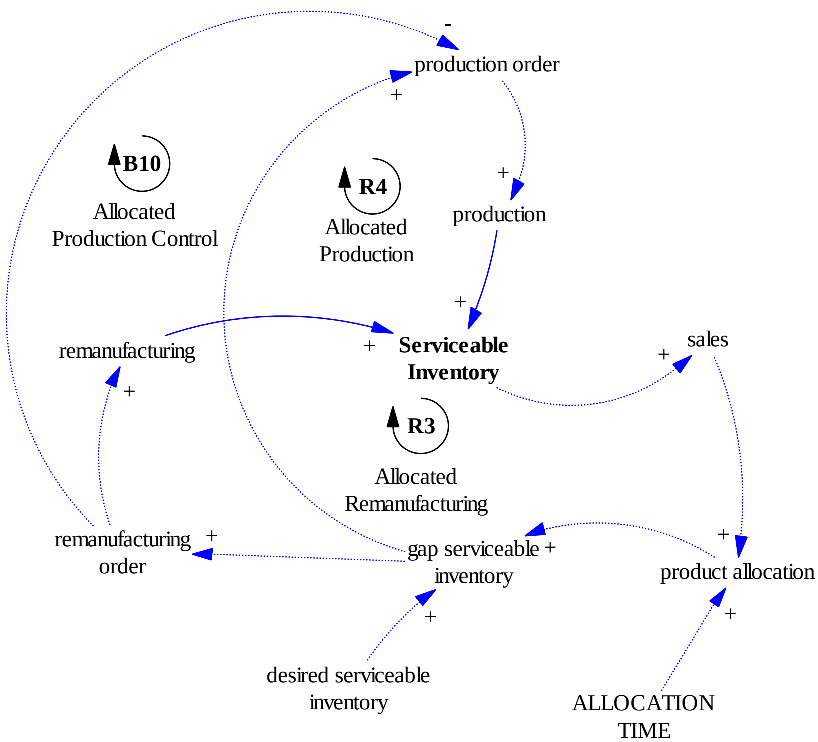


Figure 5.8: Product allocation feedback loops

Similarly, the positive loop R4, which involves the variables *sales*, *product allocation*, *gap serviceable inventory*, *production order*, *production* and *Serviceable Inventory*, can generate exponential growth in the production activity. However, the negative loops B10 and B9 (Figure 5.5) prevent the effect of R4 through a control of the *remanufacturing order* on the *production order* and of the *Serviceable Inventory* on the *gap serviceable inventory*, respectively.

5.2.3 Quantitative Modelling

The identification of stock, flow and auxiliary variables among the variables previously used to build the CLD led to the development of the SFD of the production and inventory system for remanufacturing, focusing on the remanufacturing process. The SFD representing the main stocks and flows is presented in Figure 5.9. The diagram also shows the links among the variables considered, and identifies the causal relationships described in the CLD. These relationships are used to establish mathematical equations in order to run simulations of the model and to analyse the dynamic behaviour of the remanufacturing process.

The diagram presents four stocks, which are represented by rectangles: *Collected Returns*, *Recoverable Inventory*, *Serviceable Inventory* and *Accumulated Orders*. The first three refer mainly to the remanufacturing process as they represent the accumulation of collected returns, of inspected and accepted items, and of remanufactured or produced items respectively. The last stock represents an accumulation of orders for the backorder activity. Several flow variables represented by valves, which represent the physical flow of items, feed or deplete these stocks. While the auxiliary variables shown in upper case letters represent constants, those in lower case letters represent converters used in calculations.

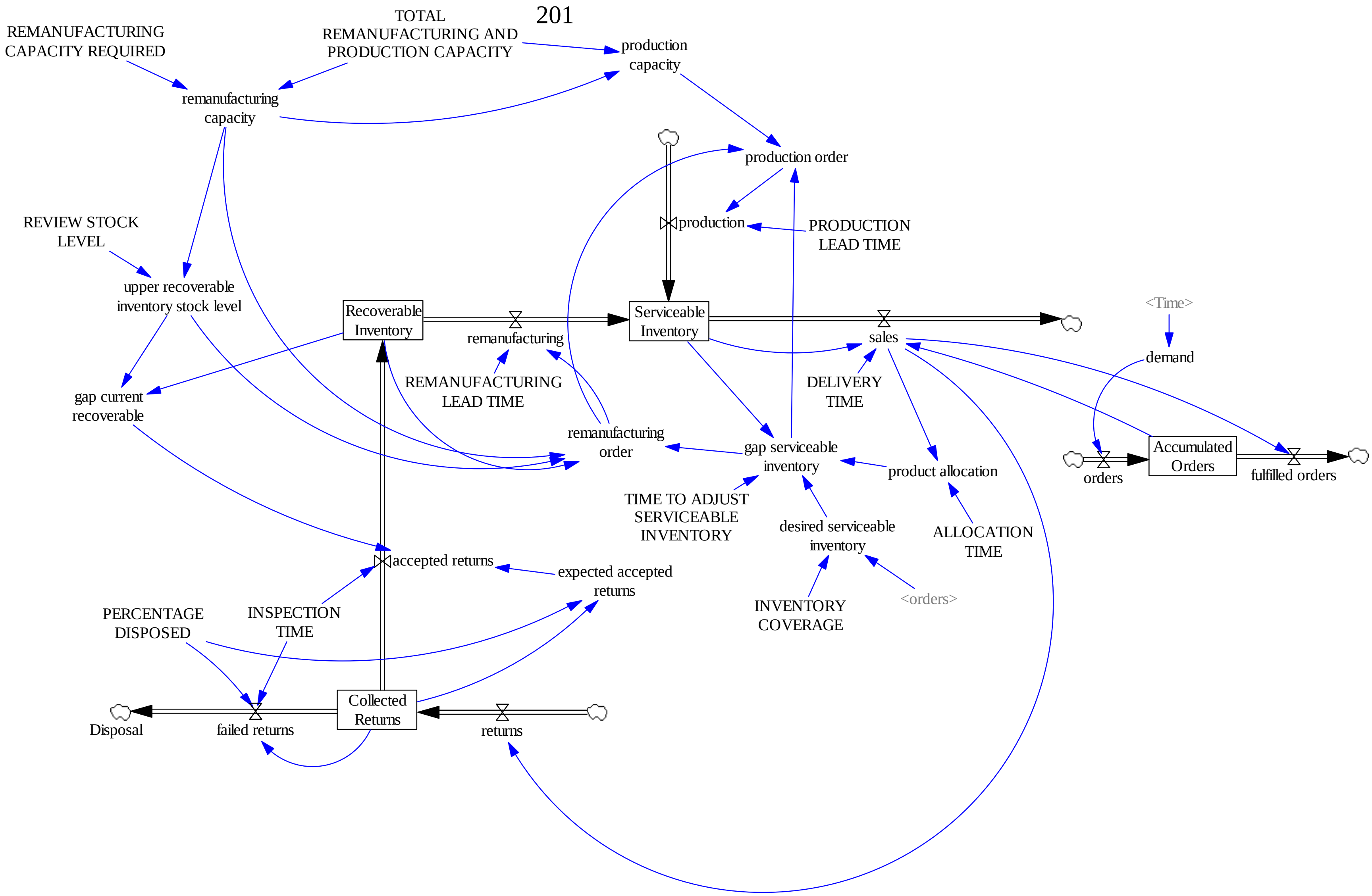


Figure 5.9: SFD for the remanufacturing process

All of the variables listed in Appendix A (Table A.2) have been used to develop the mathematical equations for the model. Table 5.1 lists these equations, which are explained further on. The equations follow the conventions of the simulation software Vensim PLE v5.6d. The constant parameters used in the equations correspond to the exogenous inputs of the SFD as well as to the initial values of the stock variables. Assumptions, which are intended to reflect as accurately as possible meaningful concepts in the real world, were used for the values of these parameters for this generic SD model. Such assumptions will be used for the sensitivity analysis of the model in Section 5.3.1.

Table 5.1: Mathematical equations for the remanufacturing process

(1)	*accepted returns = MIN (expected accepted returns, gap current recoverable) / INSPECTION TIME* Units: items/week
(2)	*Accumulated Orders = INTEG (orders – fulfilled orders, 0)* Units: items
(3)	*Collected Returns = INTEG (returns – accepted returns – failed returns, 0)* Units: items
(4)	*demand = 50 + 10 * SIN(Time)* Units: items/week
(5)	*desired serviceable inventory = orders * INVENTORY COVERAGE* Units: items
(6)	*expected accepted returns = Collected Returns * (1 – PERCENTAGE DISPOSED)* Units: items
(7)	*failed returns = (Collected Returns * PERCENTAGE DISPOSED) / INSPECTION TIME* Units: items/week
(8)	*fulfilled orders = sales* Units: items/week
(9)	*gap current recoverable = upper recoverable inventory stock level – Recoverable Inventory* Units: items
(10)	*gap serviceable inventory = (desired serviceable inventory - (Serviceable Inventory – product allocation)) / TIME TO ADJUST SERVICEABLE INVENTORY* Units: items/week

Table 5.1 – continued from previous page

(11)	*orders = demand* Units: items/week
(12)	*production = DELAY FIXED (production order, PRODUCTION LEAD TIME, 0)* Units: items/week
(13)	*production capacity = TOTAL REMANUFACTURING AND PRODUCTION CAPACITY – remanufacturing capacity* Units: items/week
(14)	*production order = IF THEN ELSE (gap serviceable inventory > remanufacturing order, MIN (production capacity, gap serviceable inventory – remanufacturing order), 0)* Units: items/week
(15)	*Recoverable Inventory = INTEG (accepted returns – remanufacturing , 0)* Units: items
(16)	*remanufacturing = DELAY FIXED (remanufacturing order, REMANUFACTURING LEAD TIME, 0)* Units: items/week
(17)	*remanufacturing capacity = REMANUFACTURING CAPACITY REQUIRED * TOTAL REMANUFACTURING AND PRODUCTION CAPACITY* Units: items/week
(18)	*remanufacturing order = IF THEN ELSE (Recoverable Inventory = upper recoverable inventory stock level :AND: gap serviceable inventory > 0, MIN (gap serviceable inventory, remanufacturing capacity), 0)* Units: items/week
(19)	*returns = DELAY FIXED (0.7 *sales, 6, 0)* Units: items/week
(20)	*sales = MIN (Accumulated Orders, Serviceable Inventory) / DELIVERY TIME* Units: items/week
(21)	*product allocation = sales * ALLOCATION TIME* Units: items
(22)	*Serviceable Inventory = INTEG (production + remanufacturing - sales, 0)* Units: items
(23)	*upper recoverable inventory stock level = remanufacturing capacity * REVIEW STOCK LEVEL* Units: items

The dynamic behaviour of the stock variables *Collected Returns*, *Recoverable Inventory*, *Serviceable Inventory* and *Accumulated Orders* is represented by a time integral of the net inflows minus the net outflows, as equations (3), (15), (22) and (2) show, respectively.

Equation (1) denotes the quantity of accepted returns during the inspection stage. The flow of these actual accepted items is represented as the minimum value between the possible quantities of accepted returns (*expected accepted returns*) and the quantity of items required by the *Recoverable Inventory* in order to issue a possible remanufacturing order (*gap current recoverable*). The result is divided by the period of time required to inspect the items (*INSPECTION TIME*). In this case, the inspection time is considered greater than or equal to the time step of the unit of time (1 week) used for the model in order to avoid a quantity of accepted returns that is greater than the available quantity of collected returns:

$$accepted\,returns(t) = \frac{MIN(\ expected\,accepted\,returns(t), gap\,current\,recoverable(t)\ )}{INSPECTION\,TIME} \quad (23)$$

Expected accepted returns at time *t*, as equation (6) shows, are equal to the total *Collected Returns* times the percentage of returns accepted for remanufacturing (*1 – PERCENTAGE DISPOSED*):

$$expected\,accepted\,returns(t) = Collected\,Returns(t) * (1 - PERCENTAGE\ DISPOSED) \quad (24)$$

Whereas, as equation (9) shows, *gap current recoverable* at time *t* is equal to the difference between the level of recoverable inventory for which a remanufacturing order can be issued (*upper recoverable inventory stock level*) and the current level of *Recoverable Inventory*:

$$gap\ current\ recoverable\,(t) = upper\ recoverable\ inventory\ stock\ level\,(t) - \\ - Recoverable\ Inventory\,(t) \tag{25}$$

Formulated in this way, equation (9) cannot assume negative values, as when the current level of recoverable inventory reaches the upper value, the gap is equal to zero. This in turn stops the flow of *accepted returns* towards the *Recoverable Inventory,* since equation (1) is equal to zero.

The variable *upper recoverable inventory stock level* is formulated using the remanufacturing capacity (equation (23)):

$$upper\ recoverable\ inventory\ stock\ level\,(t) = remanufacturing\ capacity\,(t) * \\ * REVIEW\ STOCK\ LEVEL \tag{26}$$

The objective is to use to the maximum extent the available remanufacturing activity as well as to model a pull inventory policy between *Recoverable Inventory* and *Collected Returns*. For this reason the factor *REVIEW STOCK LEVEL* is used in the formulation. It represents the periodic review interval used for the *period review method* in a pull inventory control (Ballou 2004). Specifically in this case, at every periodic review interval (*REVIEW STOCK LEVEL*) the recoverable inventory level is checked in order to define the *gap current recoverable*. The latter depends on the maximum level (*upper recoverable inventory stock level*) for the recoverable inventory. This maximum level is formulated by trying to use all of the remanufacturing capacity during the review interval which is equal to the given time period for the remanufacturing capacity (week) in order to optimise the use of remanufacturing activity.

Remanufacturing capacity is formulated as a percentage of the total system capacity through the use of *REMANUFACTURING CAPACITY REQUIRED* (equation (17)):

$$remanufacturing\ \ capacity(t) = REMANUFACTURING\ CAPACITY\ REQUIRED* \\ *\ TOTAL\ REMANUFACTURING\ AND\ PRODUCTION\ CAPACITY \quad (27)$$

Consequently, *production capacity* is equal to the difference between the total system capacity and the remanufacturing capacity (equation (13)):

$$production\ \ capacity\,(t) = TOTAL\ \ REMANUFACTURING\ \ AND\ \ PRODUCTION \\ CAPACITY\ \ -\ remanufacturing\ \ capacity\,(t) \quad (28)$$

An *IF THEN ELSE* function and the logical operator *AND* are used to define the *remanufacturing order* in the process (equation (18)). In particular, these tools determine the number of remanufacturing orders in the model. The logical expression defines the condition when the *Recoverable Inventory* level is equal to the *upper recoverable inventory stock level* and also when the *gap serviceable inventory* is greater than zero. If the condition is true, the expression returns remanufacturing orders quantity equal to the minimum value between *gap serviceable inventory* and *remanufacturing capacity*; otherwise the returned value is zero. So formulated, remanufacturing orders are generated only when both the recoverable inventory level reaches its maximum level (*upper recoverable inventory stock level*) and the serviceable inventory requires new remanufactured products to fulfil the value of the *desired serviceable inventory* level. In this way, following a pull inventory policy between *Recoverable Inventory* and *Serviceable Inventory*, only the required quantity of items will be remanufactured. A similar equation defines the production quantity and the number of production orders (*production order*) in the model (equation (14)). In this case, the condition requires that *gap serviceable inventory* is greater than *remanufacturing order*. If the condition is true, the expression returns a production reorder quantity equal to the minimum value between *production capacity* and the difference *gap serviceable inventory* minus *remanufacturing order*; otherwise the returned value is zero. Formulated in this way, production activity is used only when the remanufacturing reorders are not able to fulfil the quantity of products required by the *Serviceable Inventory*. Therefore, in this system the cheaper remanufacturing activity is a substitute for the more costly production activity.

Remanufacturing and production activity are formulated in equations (16) and (12), respectively. The remanufactured and produced quantities of items are available for storage in the *Serviceable Inventory* after a period of time from the issue of the orders (*REMANUFACTURING* and *PRODUCTION LEAD TIME*). In order to model this process the function *DELAY FIXED* is used. This function returns the value of the inputs *remanufacturing order* and *production order* delayed by the delay time, which in this case is the lead time:

$$\begin{aligned} &remanufacturing\ (t) = DELAY\ FIXED\ (remanufacturing\ order\ (t), \\ &, REMANUFACTURING\ LEAD\ TIME, 0) \end{aligned} \tag{29}$$

$$production(t) = DELAY\ FIXED(production\ order\ (t), PRODUCTION\ LEAD\ TIME, 0) \tag{30}$$

The equation (10) formulates the variable *gap serviceable inventory*, which represents the difference between the *desired serviceable inventory* level and the available *Serviceable Inventory* on hand (*Serviceable Inventory – product allocation*). The result is divided by the time period over which the system seeks to bring serviceable inventory in balance with the desired level (Sterman 2000):

$$\frac{desired\ serviceable\ inventory\ (t) - (Serviceable\ Inventory\ (t) - product\ allocation\ (t))}{TIME\ TO\ ADJUST\ SERVICEABLE\ INVENTORY} \tag{31}$$

The *desired serviceable inventory* is equal to the customer *orders* times the *INVENTORY COVERAGE* (equation (5)):

$$desired\ serviceable\ inventory\ (t) = orders\ (t) * INVENTORY\ COVERAGE \tag{32}$$

Product allocation is equal to the *sales* times the *ALLOCATION TIME* (equation (21)). The latter represents the time period for which serviceable inventory can be allocated for the sales.

$$product\ allocation\,(t) = sales\,(t) * \ ALLOCATION\ \ TIME \tag{33}$$

Demand, in this case, is formulated as a time series with a time independent base level of 50 and a seasonal component represented by the cyclical part 1*0* sin(t)* (equation (4)) : $demand\ (t) = 50 + 10 * SIN\ (Time)$. However, as *demand* is an exogenous variable different behavioural patterns and several time series components can be used in order to formulate the value of actual customer demand.

Customer *orders*, in this case, are equal to customer demand (equation (11)): $orders\,(t) = demand\ (t)$. However, *orders* can be formulated as a percentage of *demand* to account for the fact that not all possible orders (*demand*) become confirmed orders. When the confirmed orders are shipped to customers, they become *fulfilled orders* or *sales*. Equation (8) represents this process: $fulfilled\ orders\,(t) = sales\,(t)$. *Sales*, as equation (20) shows, are formulated as the minimum value between the *Accumulated Orders* and the *Serviceable Inventory*. The result is divided by the *DELIVERY TIME* which represents the time required to deliver the products to customers from the time of receiving the orders. In this case, the delivery time is considered greater than or equal to the time step of the unit of time used for the model in order to avoid the number of sales being greater than the available quantity of serviceable inventory:

$$sales\,(t) = \frac{MIN\ (\ \ Accumulated\ Orders\,(t), Serviceable\ Inventory\,(t)\ )}{DELIVERY\ TIME} \tag{34}$$

In order to formulate the returns quantity the function *DELAY FIXED* is used (equation (19)). Thus, *returns* are formulated as percentage of previous sales which becomes available after staying with the customers for a period of time (6 months in this case):

$$returns\,(t) = DELAY\ \ FIXED\,(0.7 * sales\,(t), 6, 0) \tag{35}$$

Finally, equation (7) denotes the quantity of failed returns at time *t* which are equal to the total *Collected Returns* times the *PERCENTAGE OF DISPOSAL* divided by the *INSPECTION TIME*:

$$failed\ returns(t) = \frac{Collected\ Returns(t) * PERCENTAGE\ DISPOSED}{INSPECTION\ TIME} \tag{36}$$

5.3 Model Validation

In order to validate the developed model and determine its suitability for evaluating strategies aimed at improving the performance of the system, through a simulation analysis focusing particularly on the remanufacturing process, a sensitivity analysis was undertaken. Through this sensitivity analysis we also determined whether the model displayed sensitivity to particular parameters involved in the remanufacturing process in order to use them for the simulation analysis. Moreover, a simplified approach similar to *pattern prediction testing* (Barlas 1989) for behaviour validation was applied to analysis of the case study company, which will be presented in section 5.5. Specifically for the behaviour validation, the test involved simulation of the developed remanufacturing process model in which exogenous inputs are given the values of real data. The exogenous inputs considered are the variables *demand* and *returns*, which in this case are formulated as lookup functions with specific real company data series. The simulation using these input data then generates the behaviour patterns or observed output of the model, which is seen to be a *synthetic real system* insofar as the output data are considered ‘real’. Conversely, the simulation using assumed inputs data generates the behaviour patterns or output of the model generated by a *synthetic real system*, as the output data are considered to be 'model generated'. The test then involved a comparison between the observed and the 'model-generated' output. In this way, it is possible to draw a comparison between the 'real' and the 'model-generated' behaviour patterns.

The results of the behaviour pattern validation will be presented in section 5.5, while the results of the sensitivity analysis are presented next.

5.3.1 Sensitivity Analysis

The sensitivity analysis involved changes of value for particular parameters, and comparison between the changes generated in the dynamic behaviour patterns of the modelled system and similar changes within a real system.

The analysis involved those parameters that we believe have both a high level of uncertainty with regards to the most appropriate value to use in the system and a high degree of influence on the dynamic behaviour of the remanufacturing process. These parameters are: *INVENTORY COVERAGE*, *PERCENTAGE DISPOSED*, *REMANUFACTURING CAPACITY REQUIRED*, *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY*, *REMANUFACTURING LEAD TIME* and *PRODUCTION LEAD TIME*. Specifically, the first parameter, which controls the use of a pull or push policy for the serviceable inventory, influences the dynamic behaviour of remanufacturing and production activities, which in turn influences the remanufacturing process from the collection phase. Similarly, the other parameters influence the behaviour of the entire remanufacturing process by affecting the quantity of accepted returns, the remanufacturing orders, and the flow of remanufactured and produced items towards the serviceable inventory. Moreover, due to the generality of the model, a high level of uncertainty surrounds determining the parameter values suitable for use in the system.

For the base scenario, the assumptions used to define the values of the parameters were formulated based on theory drawn from literature review and on information gained from the data collection. However, as we are analysing changes in the dynamic behaviour patterns of the system due to changes in the value of these parameters, we deemed it to be more important to enhance understanding of the dynamic behaviour of the system rather than the exact value of the parameters. The values for *INSPECTION TIME*, *REVIEW STOCK LEVEL*, *DELIVERY TIME*, *ALLOCATION TIME* and *TIME TO ADJUST SERVICEABLE INVENTORY* are assumed to be one week. This means that the time period for conducting several activities such as collection and inspection of returns, reviewing periodically the recoverable inventory level, and delivering and allocating products to customers is set at one week. *PERCENTAGE DISPOSED* is assumed to be 5%, 40% for *REMANUFACTURING CAPACITY REQUIRED* and 200 units per week for *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY*. *REMANUFACTURING* and *PRODUCTION LEAD TIMES* are set at two weeks, while *INVENTORY COVERAGE* is equal to one week. These parameter values were chosen to represent a reasonable range found in a real system in light of the generality of the model. The input for the model simulation is represented by the variable *demand* which is set using a sine wave time series as previously formulated in equation (4) in Section 5.2.3. The use of a sine wave time series for the simulation input provides a suitable level of generality for the model to cover a range of product characteristics and industries. Moreover, it is appropriate for the representation of a basic quantitative model of a dynamic real system (Kleber 2006; Sterman 2000).

Figure 5.10 shows the effect of changes in the *INVENTORY COVERAGE* on *Accumulated Orders*, which represents the backorder, and *Serviceable Inventory*, running the simulation for a time horizon of 60 weeks with a time step of one week. In this case the base scenario (*INVENTORY COVERAGE* equal to one week) defines a pull inventory policy for the system. Specifically, the desired serviceable inventory level equals the actual customer orders which in turn leads the remanufacturing and production activity to be orders driven.

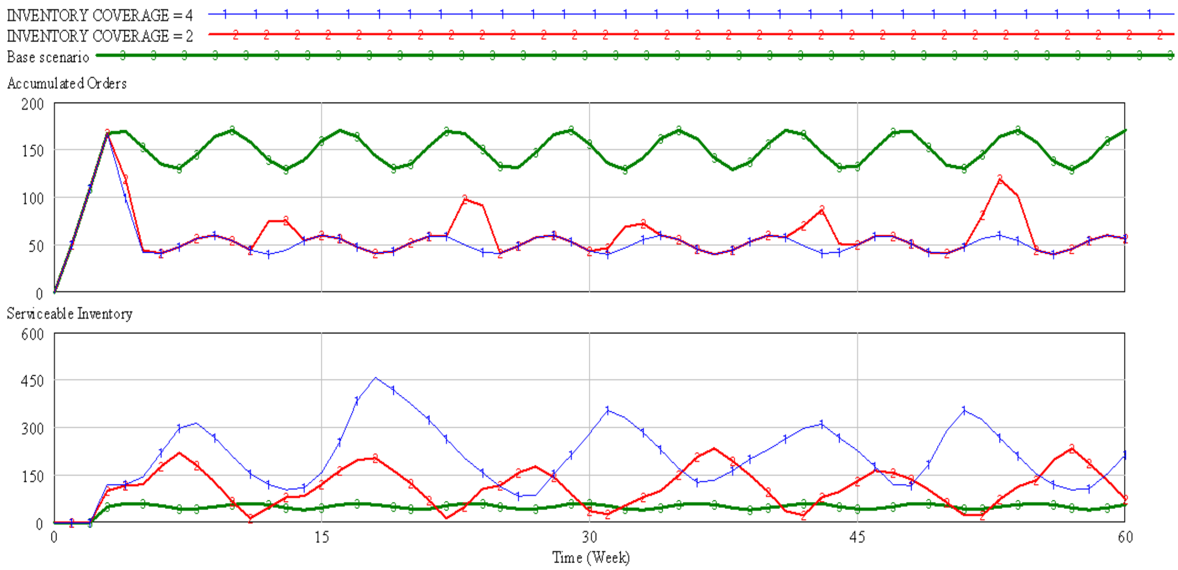


Figure 5.10: Effect of *INVENTORY COVERAGE* on the remanufacturing process

Figure 5.10 shows that an increase in *INVENTORY COVERAGE* affects the behaviour of the system as the three curves do not follow the same behavioural pattern. For example, regarding the *Accumulated Orders*, an increase in *INVENTORY COVERAGE* generates a drop in backorders when the *Serviceable Inventory* starts to overload. Moreover, for an *INVENTORY COVERAGE* equal to two weeks, the backorder does not follow a constant trend as several peaks are generated during the time horizon. This is due to a lower inventory coverage level, compared to four weeks, which involves a shortage of serviceable inventory at certain times. These changes in the values of backorder and the serviceable inventory level reflect the behaviour of a real system. Specifically, increasing the value of the analysed parameter, the system should tend to use a push strategy with a higher serviceable inventory level and a lower backorder quantity. The same behaviour is seen in the values shown by the three curves during the simulation. The increase in the serviceable inventory level is due to a larger remanufacturing and production activity aimed at bringing the serviceable inventory level in balance with a higher desired value, which in this case is not orders driven. Consequently, the decrease in backorder is due to a higher availability of inventory to immediately fill the orders.

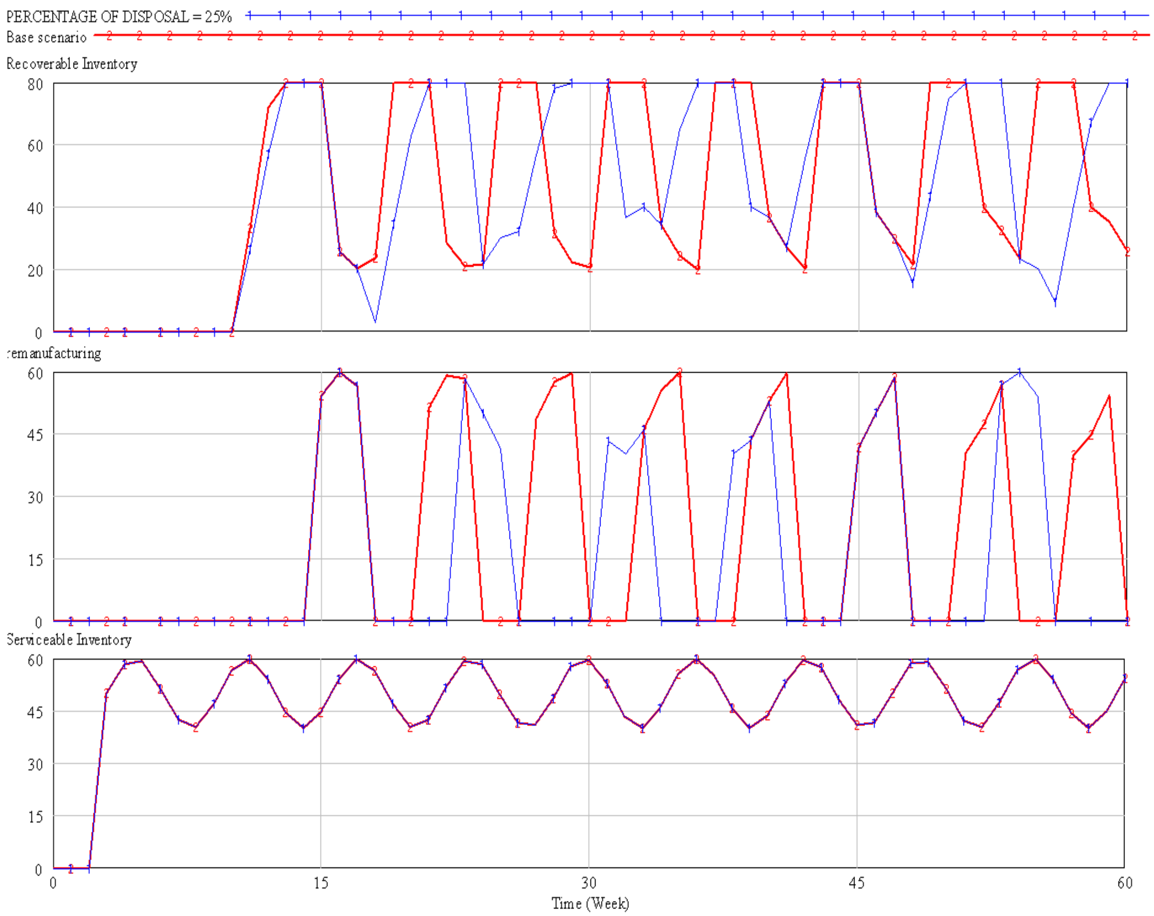


Figure 5.11: Effect of *PERCENTAGE DISPOSED* on the remanufacturing process

Changes in the *PERCENTAGE DISPOSED* show that some variables of the system such as *Serviceable Inventory* and consequently *sales* and *Accumulated Orders* are insensitive to the values of this parameter, while the variables involved in the storage of recoverable inventory and remanufacturing activity are affected by its change. The expected insensibility is due to the operations structure of the remanufacturing processes which are characterised by integration between production and remanufacturing activity. Specifically, an increase in disposed returns generates a shortage of recoverable inventory which in turn reduces remanufacturing activity. This reduction leads to an increase in production activity, which satisfies the demand for products generated by the serviceable inventory. For this reason, the latter, and consequently the sales and backorder quantity, is not affected by a possible increase in the percentage of disposed returns. Figure 5.11 shows how the model reflects such an operations structure for which an increase in *PERCENTAGE DISPOSED* reduces the rise of the *Recoverable Inventory* towards the upper level at which a remanufacturing order can be issued. Thus, the remanufacturing activity is less frequent compared to that within the base scenario. Moreover, the *Serviceable Inventory* is not affected by changes in the parameter value.

The analysis of the effects on the system of the changes in the remanufacturing capacity involved simultaneous simulations of the two parameters *REMANUFACTURING CAPACITY REQUIRED* (RE Ca) and *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY* (TC). Table 5.2 shows the parameter values and the combinations used for this simultaneous simulations analysis in which the total system capacity is able to satisfy customer orders. This is obtained by setting the values of the *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY* as greater than the time independent base level used to formulate customer orders.

Table 5.2: Capacity combinations able to satisfy customer orders

Combination	RE Ca	TC (items/week)
1	20%	500
Base scenario	40%	200
3	60%	100

The analysis initially involved only a decrease in the *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY* within the range of the shown values. For this first analysis, the system variables involved in sales activity (*Serviceable Inventory*, *sales*, *Accumulated Orders* and *returns*) were found to be insensitive to the parameter value. This is due to the ability of the total system capacity within that range to satisfy the defined customer orders. However, changes in the parameter value generated changes in the remanufacturing and production capacity, which in turn affected the recoverable inventory level. Similarly, for the second analysis, in which only an increase in the *REMANUFACTURING CAPACITY REQUIRED* was considered, the system variables involved in the sales activity were found to be insensitive to the parameter value. As was the case for *PERCENTAGE DISPOSED*, this was due to the changes in production activity aimed at balancing the changes in the remanufacturing activity. Thus, changing remanufacturing capacity, the system shows identical behaviour patterns for the system variables involved in the sales activity due to the integration between remanufacturing and production activity. However, as the total system capacity is able to satisfy the customer orders, changes in the remanufacturing capacity affected mainly the recoverable inventory level through the *upper recoverable inventory stock level*.

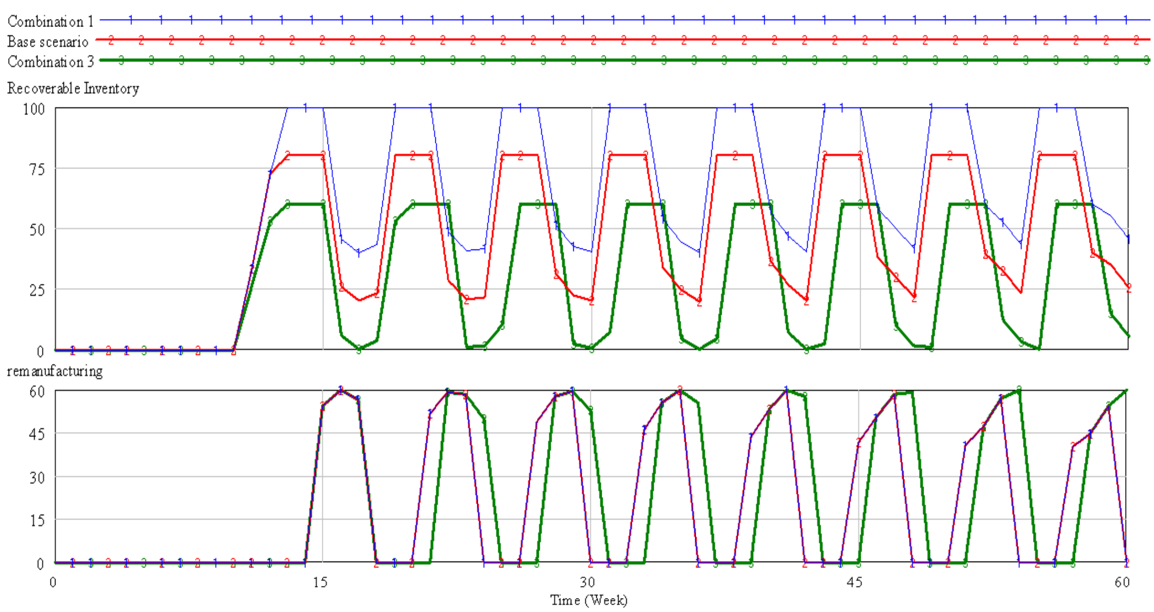


Figure 5.12: Effect of TC and RE Ca on remanufacturing activity

The third analysis involved simultaneous simulations for the combinations shown in Table 5.2. The results are shown in Figure 5.12. A reduction of the total system capacity

(Combination 3) has a greater impact on the recoverable inventory than an increase in remanufacturing capacity. This is confirmed by the decrease in the recoverable inventory level, which is possible to manage through the remanufacturing activity due to the decrease in the available total system capacity. Moreover, an increase in remanufacturing capacity cannot affect remanufacturing and consequently production activity because in the case in which the total system capacity is able to satisfy customer orders, the size of the remanufacturing orders is mainly defined by the *gap serviceable inventory*. Therefore, a reduction of the system capacity is suitable in order to reduce recoverable inventory.

Different results were obtained in the case where the total system capacity is not able to satisfy the customer orders. Table 5.3 shows the combinations for the simultaneous simulations in which the value of the *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY* is lower than the time independent base level used to formulate customer orders.

Table 5.3: Capacity combinations not able to satisfy customer orders

Combination	RE Ca	TC (items/week)
4	20%	40
5	40%	30
6	60%	20

In this case, the system variables involved in sales activity are affected by the changes in the total system capacity, as Figure 5.13 reveals. This is due to the insufficient remanufacturing and production activity, which do not have sufficient capacity to satisfy customer orders. Consequently, the system generates lower serviceable inventory levels and higher backorder levels (combination 6).

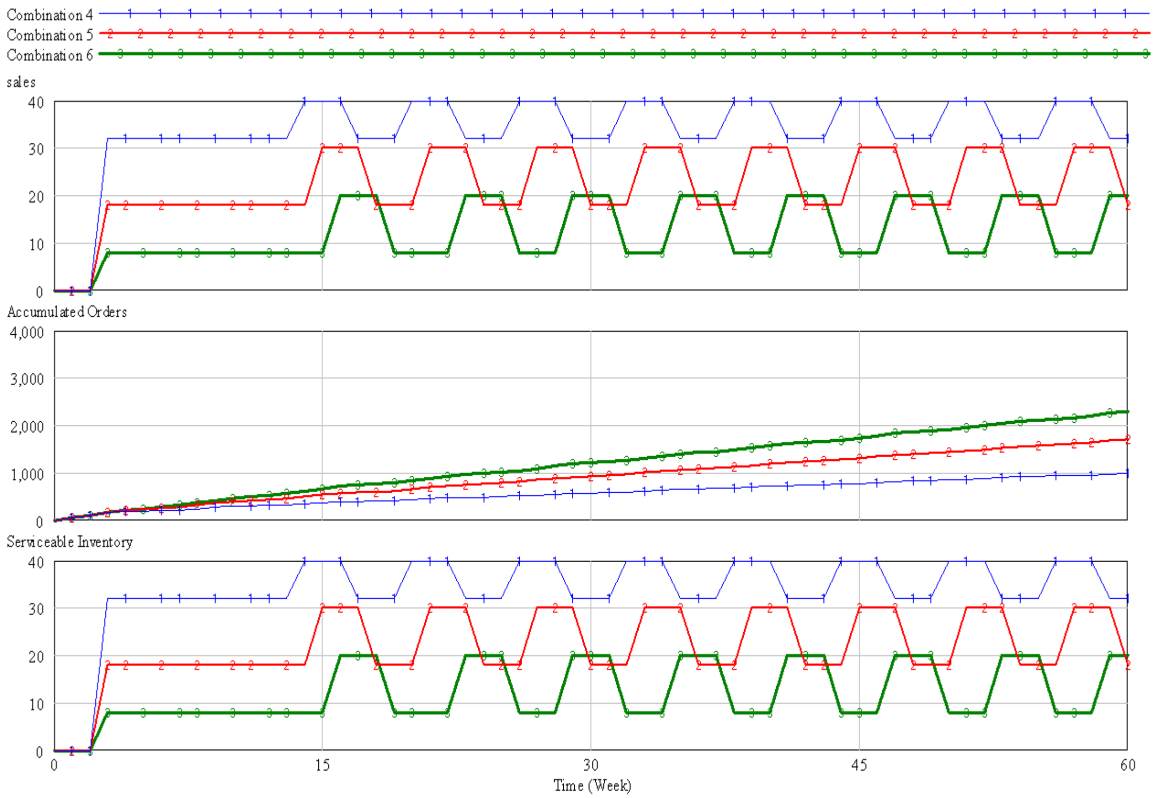


Figure 5.13: Effect of TC and RE Ca on sales activity

Due to the limited total system capacity, changes in remanufacturing capacity affect mainly the recoverable inventory level, remanufacturing and production activity. All of the items stored in the recoverable inventory are now used to generate remanufacturing orders, which are affected by the remanufacturing capacity rather than by the *gap serviceable inventory*. Consequently, *production* changes in order to achieve a balance with the remanufacturing activity. Figure 5.14 shows that in this case the remanufacturing capacity is entirely utilised in order to generate remanufacturing orders which use all of the available *Recoverable Inventory*. Moreover, the increase in remanufacturing capacity increases the remanufacturing orders size, which in turn decreases the production orders size (from combination 4 to combination 6). Specifically, for combination 6 production presents a lower orders size but a continuous activity in order to strike a balance with the remanufacturing activity in a system with insufficient total capacity.

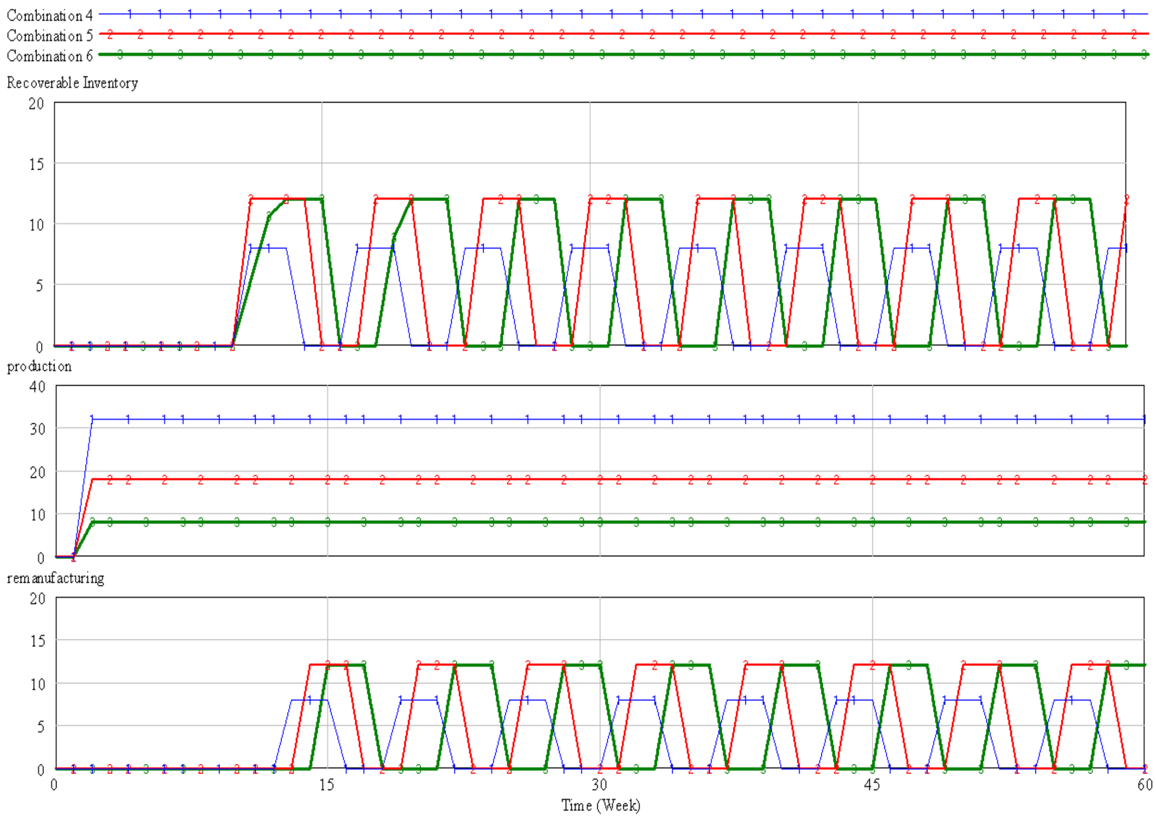


Figure 5.14: Effect of TC and RE Ca on remanufacturing orders

Following the analysis of the effects on the system of changes in the system capacity, the analysis focused on the effects on the system of changes in the remanufacturing and production lead times. Again in this case, the analysis involved simultaneous simulations of the two parameters. Table 5.4 shows the combinations used for these simultaneous simulations. However, these combinations, which involve a simultaneous increase or decrease in both types of lead times, were considered insignificant for the analysis, because of the stock results that these combinations had on the system compared to the combinations presented in Table 5.4, where remanufacturing and production lead time are increased and decreased alternatively.

Table 5.4: Combinations of remanufacturing and production lead time

Combination	*REMANUFACTURING LEAD TIME* (week)	*PRODUCTION LEAD TIME* (week)
Base scenario	2	2
7	1	2
8	2	1
9	2	3
10	3	2

Changes in production lead time mainly affect the backorder level, as Figure 5.15 shows. Specifically, by decreasing this parameter (combination 8), faster production batches flow in the serviceable inventory, which are promptly used to satisfy sales with a consequent reduction in the backorder level. However, the accumulation of slower production batches (combination 9) alongside faster remanufacturing batches (2 weeks) does not generate a large difference in the serviceable inventory level between the two combinations.

Changes in remanufacturing lead time primarily affect the recoverable inventory and consequently remanufacturing activity. A faster remanufacturing lead time (combination 7) promptly reduces the recoverable inventory level in order to generate remanufacturing batches that in turn promptly flow into the serviceable inventory in order to satisfy sales. Indeed, for a system in which a pull policy is applied to the recoverable inventory and remanufacturing has priority over production activity, the prompt reduction in the recoverable inventory generates more frequent remanufacturing batches and a lower level of backorders. Alternatively, a slower remanufacturing lead time (combination 10) tends to create longer storage times for items in the recoverable inventory due to the long time required to generate remanufacturing batches. For this reason, these flow into the serviceable inventory at a lower frequency.

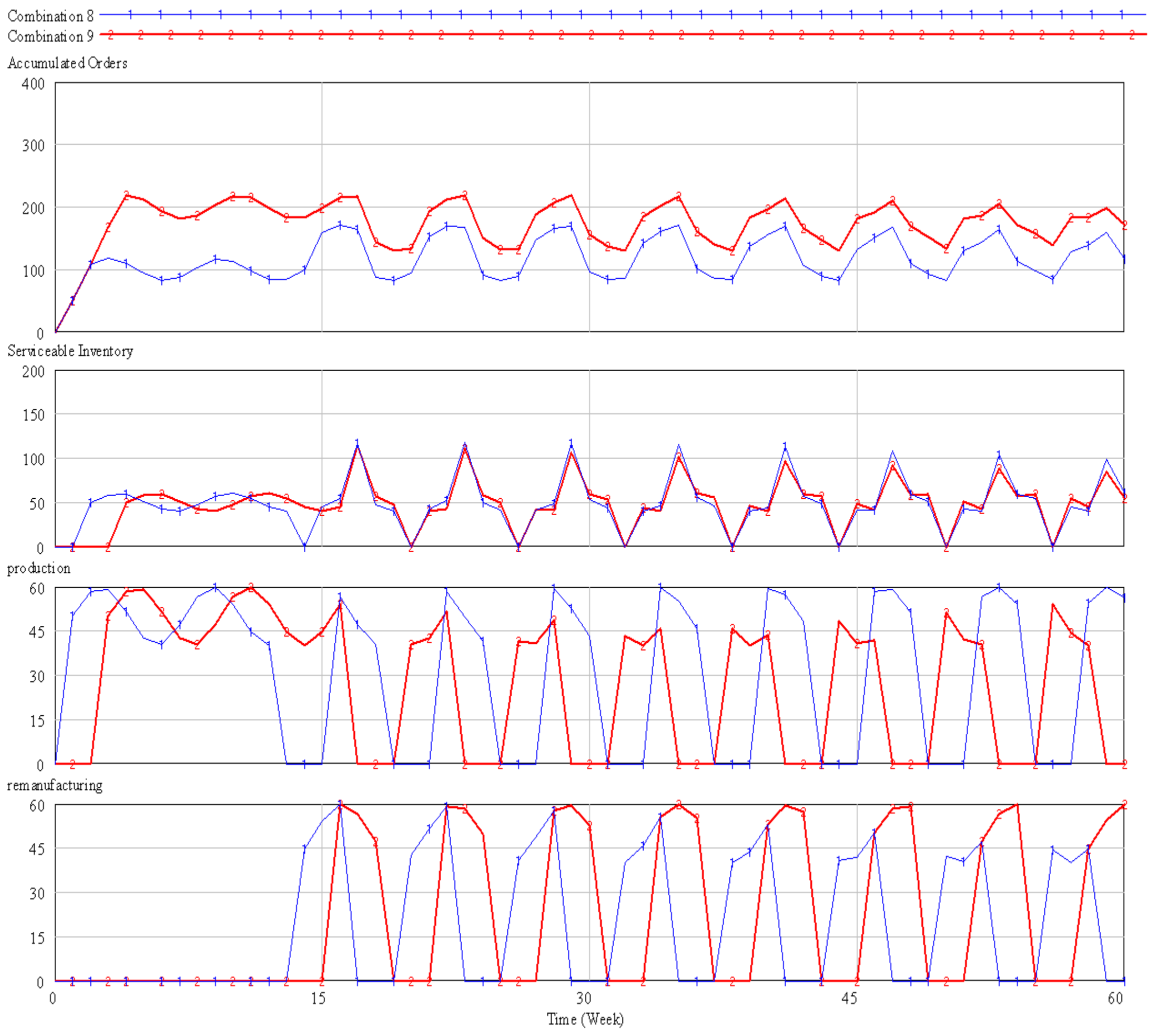


Figure 5.15: Effect of *PRODUCTION LEAD TIME*

Figure 5.16 shows the system behaviour previously described resulting from the simulation of the combinations 7 and 10. Combination 7 presents frequent reductions of the *Recoverable Inventory*, which lead to frequent remanufacturing batches and consequently frequent production batches. Alternatively, combination 10 presents less frequent reductions in the *Recoverable Inventory* where the items are longer stocked at the upper level. This in turn generates a lower frequency of the production of remanufactured batches (*remanufacturing*).

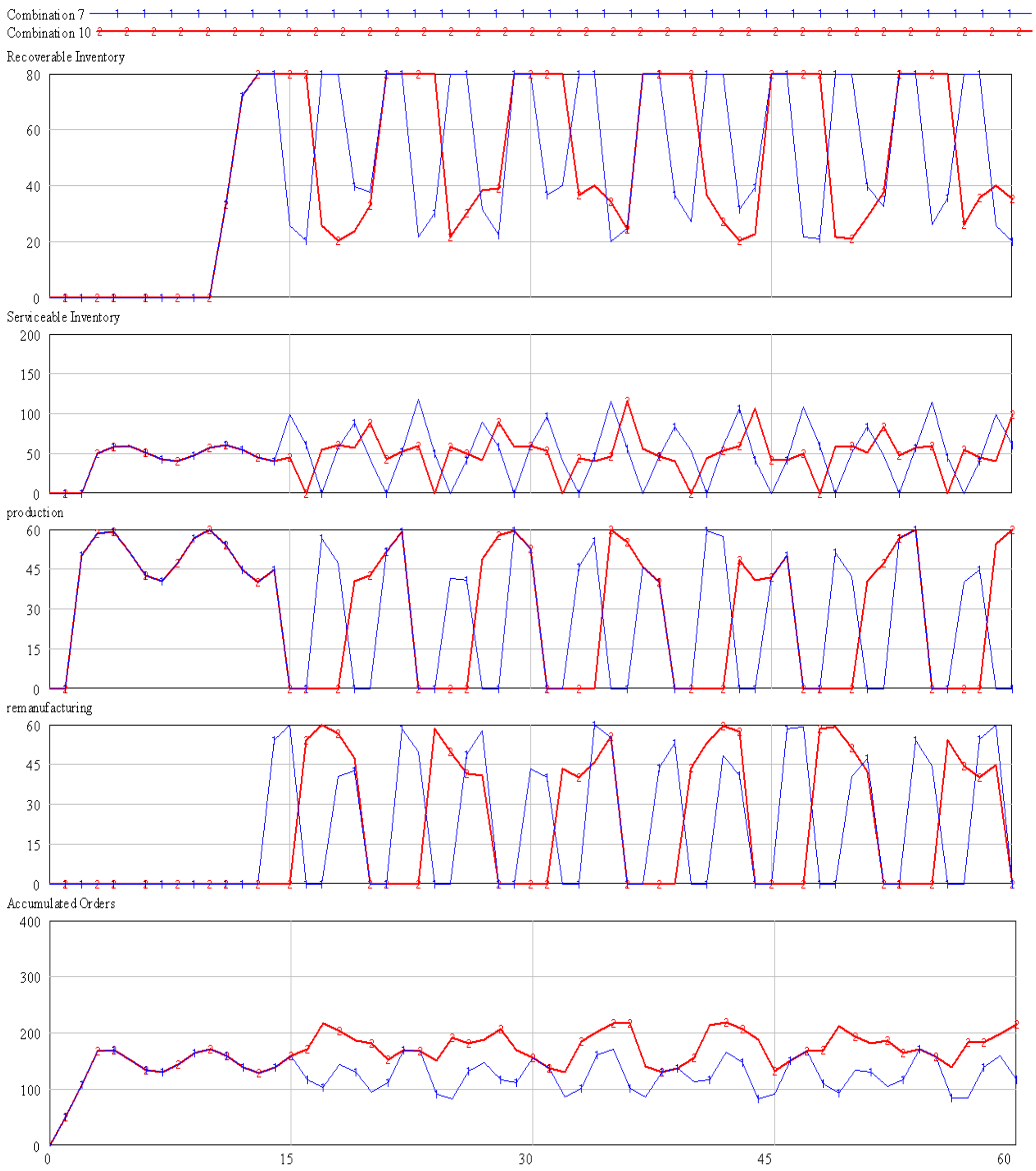


Figure 5.16: Effect of *REMANUFACTURING LEAD TIME*

5.3.2 Discussion

Based on the results of the sensitivity analysis we identified that the changes in the dynamic behaviour patterns of the model resulting from changes in the value of the considered parameters fairly accurately correspond to the available knowledge of real-world systems. For this reason, we considered the model suitable for evaluating strategies aimed at improving the performance of the system, through a simulation of scenarios focusing particularly on the remanufacturing process. In particular, these scenarios involve changes in the value of those parameters to which the model's dynamic behaviour patterns were found to be sensitive in the sensitivity analysis. These parameters are: *INVENTORY COVERAGE*, *REMANUFACTURING CAPACITY REQUIRED*, *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY*, *REMANUFACTURING LEAD TIME* and *PRODUCTION LEAD TIME*. We excluded *PERCENTAGE DISPOSED* as some variables, particularly in relation to sales activity, were found to be insensitive to the values of this parameter. Moreover, this parameter is linked to inspection company policies, which are excluded from consideration in this research.

5.4 Simulation of Scenarios for the Remanufacturing Process

The simulation of scenarios regarding the modelled remanufacturing process was developed in order to evaluate strategies aimed at improving the performance of the production and inventory system for remanufacturing. Specifically, we analysed the evolution of a particular measure of performance of the system affected by changes in the dynamic behaviour of the remanufacturing process. The changes in the latter were generated through the development of scenarios or events that intervene within the process. Such scenarios were obtained by changing the value of those particular parameters to which the model showed sensitivity, as revealed in the sensitivity analysis.

The choices regarding the measure of performance and base scenario used for the simulation analysis are discussed first. The development of the scenarios is then outlined and the simulation results presented, from which several observations regarding the evaluation of strategies to improve the performance of the system were obtained.

5.4.1 Performance Measure

The measure of performance employed for the simulation analysis of the modelled remanufacturing process was the total cost of production, inventory, remanufacturing and backorder activities. Specifically, this total system cost was obtained by the sum of several operational costs. These are the set-up costs for each production and remanufacturing order, the remanufacturing and production cost, the holding cost for the recoverable and serviceable inventory, and the backordering cost. A similar system cost has previously been used by several authors to analyse production\remanufacturing and inventory control strategies in the remanufacturing process (van der Laan & Salomon 1997; van der Laan, Salomon & Dekker 1999). However, in this case the disposal cost for the recoverable inventory is not considered as the model excludes consideration of a planned disposal of recoverable items. Moreover, in contrast to the total system cost used in section 4.4.1, in this case the remanufacturing and production costs are considered. This is due both to the use of remanufacturing capacity which affects the level of recoverable inventory through the *upper recoverable inventory stock level* and the use of an *INVENTORY COVERAGE* which indirectly affects the remanufacturing and production orders. In this case certain inventory decisions affect the remanufacturing and production activity in terms of quantity of items to be remanufactured and produced. The analysis focused on this particular total system cost which excluded the collection and inspection/disposal costs.

The formulation of both the total production and inventory cost of remanufacturing and of the operational costs is shown in Table 5.5. Assumptions were made regarding the values of the parameters according to the theoretical basis obtained from the literature review.

Table 5.5: Formulation of total system cost and operational costs

set-up cost per remanufacturing order = 20 Units: $/order
set-up cost per production order = 50 Units: $/order
number of production order = IF THEN ELSE(production order>0, production order/production order , 0) Units: order
number of remanufacturing order = IF THEN ELSE(remanufacturing order>0, remanufacturing order/remanufacturing order, 0) Units: order
*set-up costs = number of production order * set-up cost per production order + number of remanufacturing order * set-up cost per remanufacturing order* Units: $
backordering unit cost = 5 Units: $/items
*backordering cost = Accumulated Orders * backordering unit cost* Units: $
unit recoverable holding cost per time unit = 0.5 Units: $/items
*recoverable holding costs = Recoverable Inventory * unit recoverable holding cost per time unit* Units: $

Table 5.5 – continued from previous page

unit serviceable holding cost per time unit = 0.8 Units: $/items
*serviceable holding costs = Serviceable Inventory * unit serviceable holding cost per time unit* Units: $
remanufacturing cost per product per time unit = 40 Units: $/items
production cost per product per time unit = 100 Units: $/items
*remanufacturing cost = remanufacturing * remanufacturing cost per product per time unit* Units: $
*production cost = production * production cost per product per time unit* Units: $
total cost = set-up costs + remanufacturing cost + production cost + recoverable holding costs + serviceable holding costs + backordering cost Units: $

The formulations of both the *set-up costs* and the *recoverable* and *serviceable holding cost* are similar to their equivalent formulations previously defined in section 4.4.1. The *backordering cost* is obtained through the multiplication of the unit cost for a backorder and the quantity of backorders (*Accumulated Orders*). The unit cost for a backorder is set to a low value in order to not overly penalise the pull policy which basically works on backorders. However, this value can change given different product characteristics and industry contexts. The *remanufacturing* and *production cost* is defined through the multiplication of the equivalent cost per product per time unit and the remanufactured and produced quantity respectively. The *remanufacturing cost per product per time unit* is considered equal to 40% of the cost of production (Mitra 2007).

5.4.2 Base Scenario

The base scenario employed for the simulation of scenarios uses the same parameter values previously considered in Section 5.3.1 for the sensitivity analysis. However, the exogenous variable *demand* is not set as only a seasonal component (sine wave time series), but also includes a trend and random component. In this way, the generality of the model is increased to cover a range of product characteristics and industries. The variable *demand* is then formulated as:

$$demand\ (t) = 10 + 0.2 * Time + 5 * SIN\ (Time) + RANDOM\ UNIFORM\ (10,20,2) \quad (37)$$

In the equation, which involves the *additive model* for the form of the time series (Dilworth 2000), several components are added to estimate the *demand*. Specifically, the sum of the first two factors represents the trend component, while the third and fourth factors represent the seasonal and random components, respectively. However, the cyclical component, which is usually attributed to a business cycle, is not considered in the formulation due to the lengthy period of repetition it requires. Usually, 15 or 20 years of data are required to determine and describe the cyclical component (Dilworth 2000) which, in this case, does not affect the simulation of the model for a time horizon of 60 weeks.

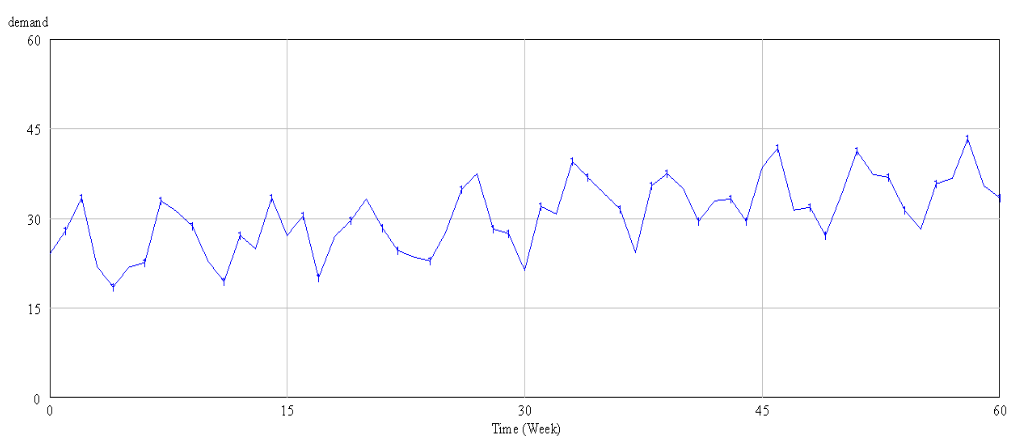


Figure 5.17: *demand* (base scenario)

The evolution of demand over the planning horizon in which a positive trend is considered is shown in Figure 5.17.

5.4.3 Scenarios Derived from the Remanufacturing Process

The various scenarios employed for the simulation analysis were obtained through changes in the value of particular parameters. Such parameters are those to which, through the sensitivity analysis, the model showed sensitivity. Moreover, as previously mentioned in Section 5.3.1, they affect the dynamic behaviour of the modelled remanufacturing process. These parameters are: *INVENTORY COVERAGE* (IC), *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY* (TC), *REMANUFACTURING CAPACITY REQUIRED* (RE Ca), *REMANUFACTURING LEAD TIME* (RLT) and *PRODUCTION LEAD TIME* (PLT).

The first simulation results revealed the effect of various levels of *INVENTORY COVERAGE*, *TOTAL REMANUAFCTURING AND PRODUCTION CAPACITY* and *REMANUFACTURING CAPACITY REQUIRED* on the measure of performance employed. The aim was to analyse the effects of different capacity levels on the modelled remanufacturing process in which push and pull policies are applied. For this purpose, 3 levels of *INVENTORY COVERAGE*, 5 levels of *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY* and 4 levels of *REMANUFACTURING CAPACITY REQUIRED* were examined. Table 5.6 lists the parameter values used for the analysis, which involved a total of 60 scenarios. Furthermore, as we are analysing the changes in the dynamic behaviour of the remanufacturing process under different scenarios, the exact value of the parameters was not seen as of equal importance to the understanding of these changes. For this reason, we adopted values for the parameters that corresponded as much as possible to a meaningful reflection of real-world scenarios for a broad range of products.

Table 5.6: Parameter values of system capacity and inventory coverage

Scenarios	IC (week)	TC (items/week)	RE Ca
Pull remanufacturing policy	1	10, 30, 50, 70, 90	20%, 40%, 60%, 80%
Push remanufacturing policy	2	10, 30, 50, 70, 90	20%, 40%, 60%, 80%
	3	10, 30, 50, 70, 90	20%, 40%, 60%, 80%

The various scenarios are characterised by a different number of weeks for the value of *INVENTORY COVERAGE*. Specifically, one week identifies a *pull remanufacturing policy* as the *desired serviceable inventory*, which indirectly through the *gap serviceable inventory* affects the remanufacturing and production activity, is equal to the number of customer orders. In this case the remanufacturing and production activity works on a make-to-order process. Alternatively, two and three weeks define a *push remanufacturing policy* as the remanufacturing and production activity, which is affected by a *desired serviceable inventory* higher than the actual customer orders, which works to hold products in the serviceable inventory, generating a make-to-stock process. The scope of the analysis is not to define the optimal policy for the system, for which we would require particular information on product and industry characteristics but rather to analyse for different remanufacturing policies how the total and operational costs are affected by various changes in the capacity level.

Figure 5.18 presents the evolution of the average total cost for various and simultaneous simulated values of *INVENTORY COVERAGE* and *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY*, on the basis of a *REMANUFACTURING CAPACITY REQUIRED* that is equal to 60%. The numerical results are presented in Table 5.7.

Table 5.7: Average total cost changing IC and TC

TOTAL REMANUFACTURING AND PRODUCTION CAPACITY	10	30	50	70	90
INVENTORY COVERAGE					
1	$4008	$3424	$2933	$2649	$2666
2	$4008	$3399	$2808	$2514	$2560
3	$4008	$3399	$2831	$2625	$2583

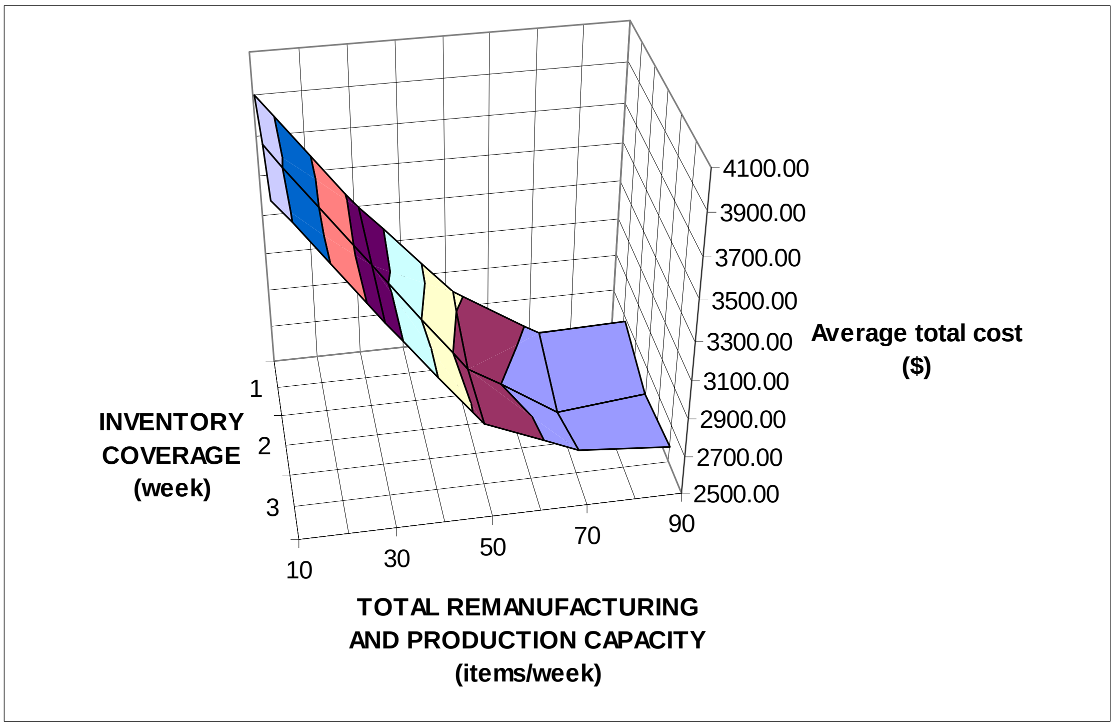


Figure 5.18: Evolution of the average total cost changing IC and TC

The first observation highlights an increase in the average total cost if the *INVENTORY COVERAGE* is reduced from a value of two weeks to one. This result is due to the larger quantity of backorders which is generated when the system moves from a push to a pull remanufacturing policy. Due to the remanufacturing and production lead time, these backorders accumulate during the planning horizon and consequently generate a higher positive trend in the backorder costs, which in turn increases the average value of the total cost. This observation does not prove that a push system should be preferred to a pull system, partly because increasing the *INVENTORY COVERAGE* from two to three weeks means the average value of the total cost starts to increase again. The surface chart shows this trend which is not monotonically constant for higher values of total system capacity (50, 70 and 90). Moreover, all of the operational costs, in particular production, remanufacturing, set-up and serviceable holding cost, except for the backordering, seem to prefer the pull to the push system, as Table 5.8 reveals. For this reason, as the observation is valid for all considered values of *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY* except the lowest one, in the case of a pull remanufacturing system with adequate system capacity the analysis and the consequent strategies that ought to be applied should focus on the remanufacturing and production lead time rather than on the system capacity. Changes in the lead times affect the time required to produce or remanufacture products and consequently store them as serviceable inventory. These changes in turn can reduce the time needed to satisfy sales and consequently the accumulation of backorders.

Table 5.8: Average operational costs changing IC and TC

TOTAL REMANUFACTURING AND PRODUCTION CAPACITY	**10**	**30**	**50**	**70**	**90**
INVENTORY COVERAGE	remanufacturing cost				
1	$94	$283	$460	$511	$511
2	$94	$283	$472	$578	$584
3	$94	$283	$472	$567	$581
	production cost				
1	$386	$1132	$1344	$1482	$1631
2	$386	$1160	$1908	$1635	$1689
3	$386	$1160	$1934	$1746	$1718
	set-up cost				
1	$58	$57	$52	$38	$38
2	$58	$57	$57	$46	$42
3	$58	$57	$57	$48	$40

Table 5.8 – continued from previous page

	serviceable holding cost				
1	$5	$14	$19	$21	$22
2	$5	$14	$27	$41	$42
3	$5	$14	$29	$58	$62
	recoverable holding cost				
1	$1	$3	$7	$10	$15
2	$1	$3	$6	$9	$13
3	$1	$3	$6	$10	$14
	backordering cost				
1	$3462	$1932	$1049	$584	$447
2	$3462	$1878	$335	$202	$187
3	$3462	$1878	$330	$193	$165

The second observation illustrates a significant increase in the average total cost for both pull and push policy, reducing total system capacity. Moreover, for both policies the system presents the same behaviour if the total capacity drops to the lowest value with a consequent indifference of the system to the policy used. This result is due to the reduction of the total capacity, which means the remanufacturing and production activity cannot fulfil the quantity of products required by the serviceable inventory (*gap serviceable inventory*). The result is that the system is less responsive to customer orders and the average total cost significantly increases because of the larger quantity of backorders. The latter is generated by the limited total system capacity which is unable to avoid the accumulation of customer orders during the planning horizon. Moreover, the difference between the limited capacity and the requirements of the serviceable inventory generates a lower and more frequent level of remanufacturing and production activity. For this reason, the results in Table 5.8 show a decrease in the cost of those activities reduced by the limited capacity such as remanufacturing, production and recoverable and serviceable inventory, and an increase in the cost of those activities characterised by a higher frequency such us number of orders (set-up costs). However, an increase in the cost of the production activity (*TOTAL REMANUFACTURING AND PRODUCTION CAPACITY* = 50, *INVENTORY COVERAGE* = 2 and 3) results if its capacity is able to substitute the reduced remanufacturing capacity. Conversely, the production cost decreases when limited capacity reduces its activity.

The second observation suggests that a reduction of total system capacity leads to a lower differentiation between the pull and push policies, as Figure 5.18 indicates. By reducing the value of the total capacity, in particular to the lowest value, the surface chart tends to be constant for each value of *INVENTORY COVERAGE*. The same observation is highlighted in Tables 5.7 and 5.8, which show that for the lowest total system capacity the average total and operational costs have the same value for both the pull and push policies. This result is due to the significant reduction in total system capacity, which in turn generates a "bottleneck" for the remanufacturing and production activity. The "bottleneck" generates rigidness in the system which, moreover, results in a remanufacturing and production capacity that is independent of the assumed value of *INVENTORY COVERAGE*. For this reason, in this case the tendency of the system is to use the full capacity of the remanufacturing and production process in order to maintain continuous remanufacturing and production activity, which is independent of the adoption of either a pull or push policy.

The second observation is valid for each level of *REMANUFACTURING CAPACITY REQUIRED*. Figures 5.19 and 5.20, similarly to Figure 5.18, represent the evolution of the average total cost referring to a *REMANUFACTURING CAPACITY REQUIRED* equal to the minimum value (20%) and the maximum value (80%), respectively. Both charts reveal a similar behavioural pattern to that in Figure 5.18. For this reason, changes in the percentage of capacity allocated to the remanufacturing activity do not affect the behavioural pattern of the average total cost for the remanufacturing process where the pull and push policy are applied. However, this does not mean that changes in remanufacturing capacity do not affect the total cost and operational costs. Figures 5.19 and 5.20, and their related Tables, show a quicker increase in the average total cost for the higher *REMANUFACTURING CAPACITY REQUIRED*, reducing total system capacity. This quicker increase in average total cost is due to the recoverable inventory level curbing the remanufacturing activity through the *upper recoverable inventory stock level* (recoverable inventory level at which it is possible to produce a remanufacturing batch). For this reason, a higher capacity allocated to remanufacturing, which in turn reduces the capacity of the not curbed production, generates a “bottleneck” in the system and consequently raises total costs. In order to reduce this total cost and at the same time increase the cheaper remanufacturing as a substitute for production activity, this last observation suggests increasing the quantity of returns and reducing the lead times associated with remanufacturing activity, such as inspection time and remanufacturing lead time. In this way, a faster increase in the recoverable inventory can generate greater remanufacturing activity, which through reduced lead times can promptly satisfy the serviceable inventory requirements. However, it would be appropriate to analyse the changes in the costs associated with an increase in the quantity of returns and lead times.

Table 5.9: Average total cost changing IC and TC, RE Ca = 20%

TOTAL REMANUFACTURING AND PRODUCTION CAPACITY	**10**	**30**	**50**	**70**	**90**
INVENTORY COVERAGE					
1	\$3946	\$3325	\$3214	\$3129	\$3035
2	\$3946	\$3214	\$3183	\$3018	\$2978
3	\$3946	\$3214	\$3255	\$3076	\$3080

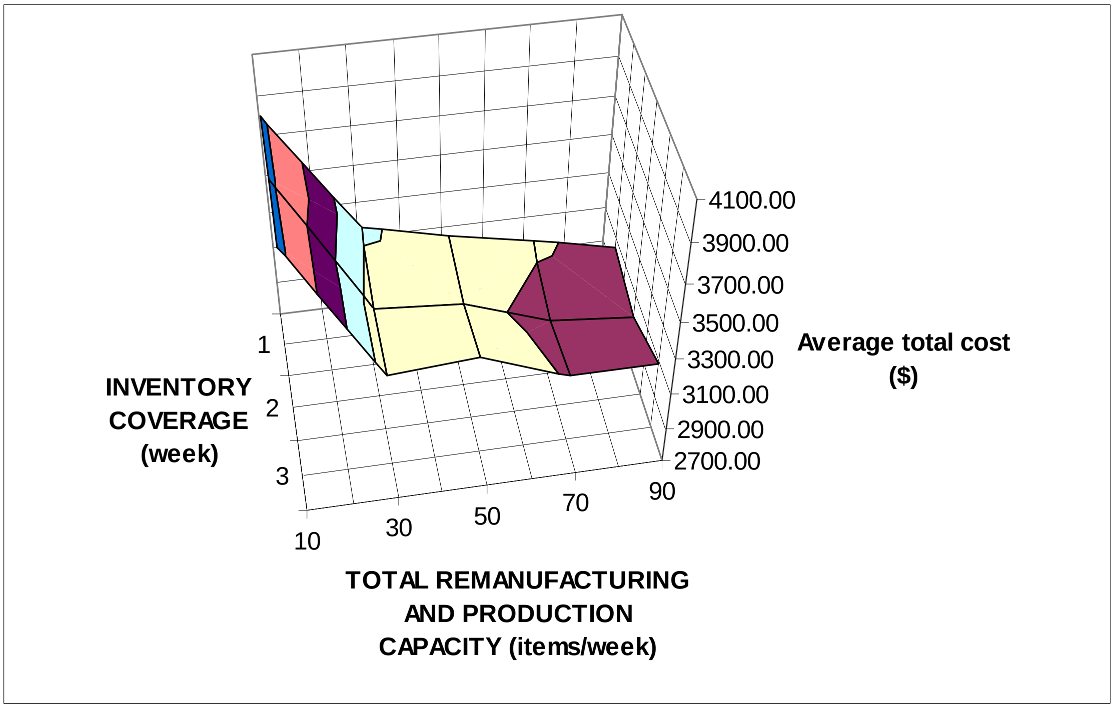


Figure 5.19: Evolution of the average total cost changing IC and TC, RE Ca = 20%

Regarding the first observation, a larger allocation of the capacity to remanufacturing activity (*REMANUFACTURING CAPACITY REQUIRED* = 80%) can penalise the pull policy for higher values of *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY* (50, 70 and 90). As Figure 5.20 and Table 5.10 show, an increase in the *INVENTORY COVERAGE* results in the average total costs monotonically decreasing. The reason for this effect is that the system gives priority to remanufacturing over production activity. In this way, for a higher total system capacity a larger remanufacturing capacity generates more remanufacturing than costly production activity. This reduction of production costs, combined with a push policy, which in turn reduces the quantity of backorders, decreases the average total cost.

Table 5.10: Average total cost changing IC and TC, RE Ca = 80%

TOTAL REMANUFACTURING AND PRODUCTION CAPACITY	10	30	50	70	90
INVENTORY COVERAGE					
1	$4127	$3795	$3581	$3296	$3103
2	$4127	$3763	$3419	$3175	$2941
3	$4127	$3763	$3400	$3055	$2805

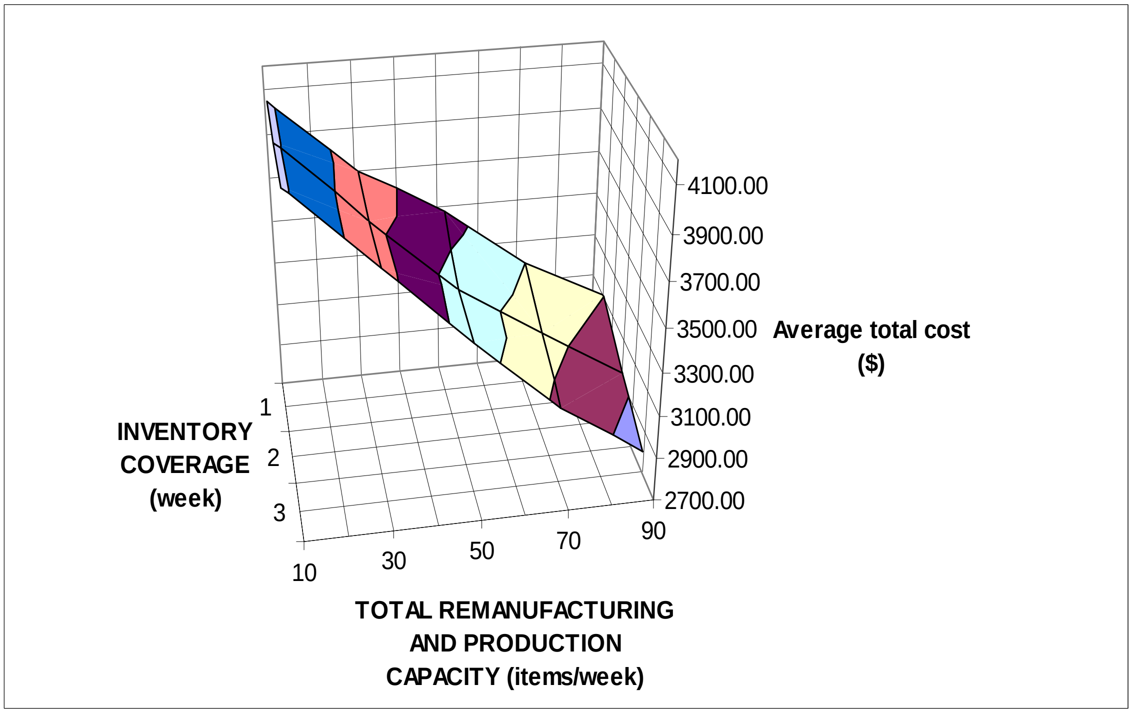


Figure 5.20: Evolution of the average total cost changing IC and TC, RE Ca = 80%

The next simulation results refer to the effect of various levels of *INVENTORY COVERAGE* (IC), *REMANUFACTURING LEAD TIME* (RLT) and *PRODUCTION LEAD TIME* (PLT) on the measure of performance employed. Table 5.11 lists the parameter values used for this analysis. In particular, the system was examined under 3 levels of *INVENTORY COVERAGE*, 3 levels of *REMANUFACTURING LEAD TIME* and 3 levels of *PRODUCTION LEAD TIME*, for a total of 27 scenarios. The *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY* and the *REMANUFACTURING CAPACITY REQUIRED* were set at 50 (items/week) and 60%, respectively. In this case, the objective was to analyse the effects of different remanufacturing and production lead times for push and pull remanufacturing policies.

Table 5.11: Parameter values for several scenarios of lead time and inventory coverage

Scenarios	IC (week)	RLT (week)	PLT (week)
Pull remanufacturing policy	1	4, 2, 0.5	4, 2, 0.5
Push remanufacturing policy	2	4, 2, 0.5	4, 2, 0.5
	3	4, 2, 0.5	4, 2, 0.5

The findings of this simulation are partially confirmed by similar observations drawn from the computational experiments within previous studies (Kiesmuller 2003; van der Laan, Salomon & Dekker 1999). However, these researchers used different models with different strategies and parameter analyses.

Figure 5.21 presents the evolution of the average total cost for various and simultaneous simulated values of *INVENTORY COVERAGE* and *REMANUFACTURING LEAD TIME*, referring to a *PRODUCTION LEAD TIME* equal to ½ week. The numerical results are presented in Table 5.12.

Table 5.12: Average total cost changing IC and RLT, PLT = 0.5

REMANUFACTURING LEAD TIME	**0.5**	**2**	**4**
INVENTORY COVERAGE			
1	$2842	$2884	$2950
2	$2706	$2710	$2772
3	$2748	$2752	$2800

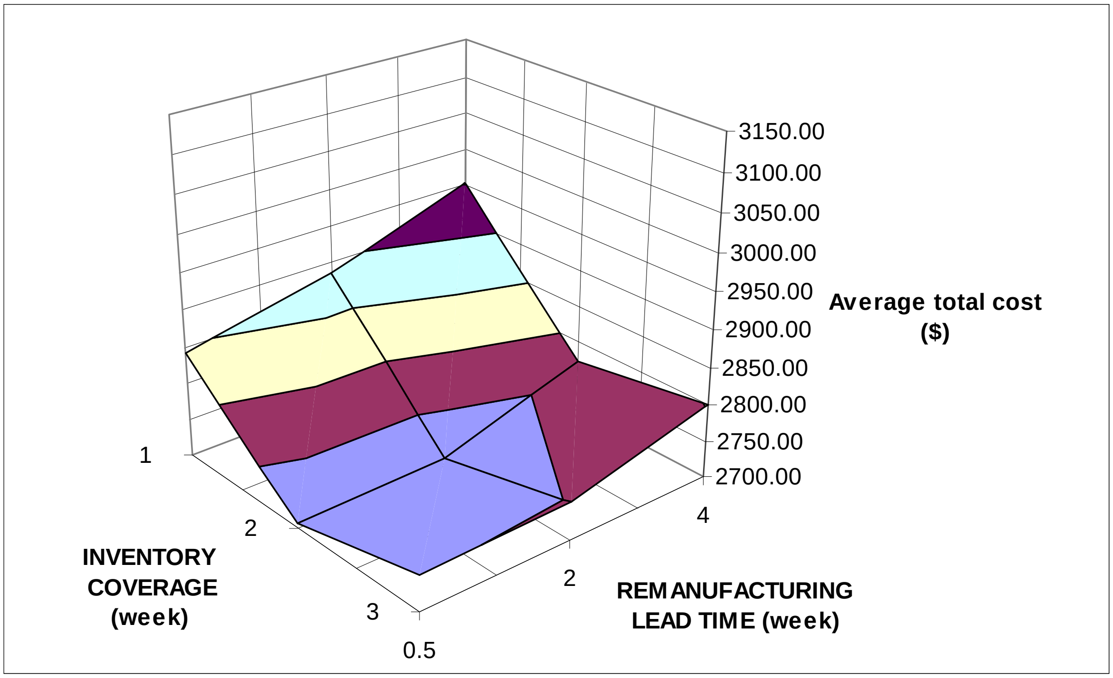


Figure 5.21: Evolution of the average total cost changing IC and RLT, PLT = 0.5

The first observation illustrates a reduction of the average total cost for both pull and push policy by decreasing the remanufacturing lead time. In particular, for the pull policy the reduction is greater. This result is due not only to an eventual reduction of the backorders quantity but also to a faster and more frequent remanufacturing activity, which in turn reduces the reliance on the more expensive production activity. Another result, similar to the first observation in the analysis of the *TOTAL REMANUFACTURING AND PRODUCTION CAPACITY*, illustrates a non-monotonic surface chart if the *INVENTORY COVERAGE* increases. Specifically, as the system changes from a pull to a push policy (*INVENTORY COVERAGE* = 2 weeks), a smaller quantity of backorders is generated, which in turn decreases the average total costs. However, increasing further the *INVENTORY COVERAGE* (*INVENTORY COVERAGE* = 3 weeks), the operational costs and consequently the average total cost start to increase again.

The second observation highlights for both policies a larger increase in the total cost by increasing the production lead time than an equivalent increase in the remanufacturing lead time. The same result was obtained in a similar study conducted by van der Laan, Salomon and Dekker (1999), yet the model and modelling approach they used were different from those adopted in this research. Table 5.13 and Figure 5.22 show the evolution of the average total cost when the production lead time has a value equal to 4 weeks. The comparison between the values presented in Tables 5.13 and 5.12 reveals a larger cost increase for both policies when the *PRODUCTION LEAD TIME* changes from ½ to 4 weeks than the cost increase for the same change in *REMANUFACTURING LEAD TIME*. This result is because of the independence of the production activity from the recoverable inventory and quantity of returns. In contrast to the remanufacturing activity, production is constrained only by its capacity. For this reason, a reduction in the production lead time generates faster production batches which accumulate in the serviceable inventory, thus reducing the backorders quantity. Conversely, an equal reduction in the remanufacturing lead time has a lesser effect on the backorders as the remanufacturing activity is curbed by the recoverable inventory level and returns quantity through the *upper recoverable inventory stock level*. However, as the system gives priority to remanufacturing activity, a reduction in remanufacturing lead time does impact on the backorders.

Table 5.13: Average total cost changing IC and RLT, PLT = 4

REMANUFACTURING LEAD TIME	**0.5**	**2**	**4**
INVENTORY COVERAGE			
1	$3006	$3101	$3126
2	$2954	$3000	$3038
3	$2950	$2975	$3021

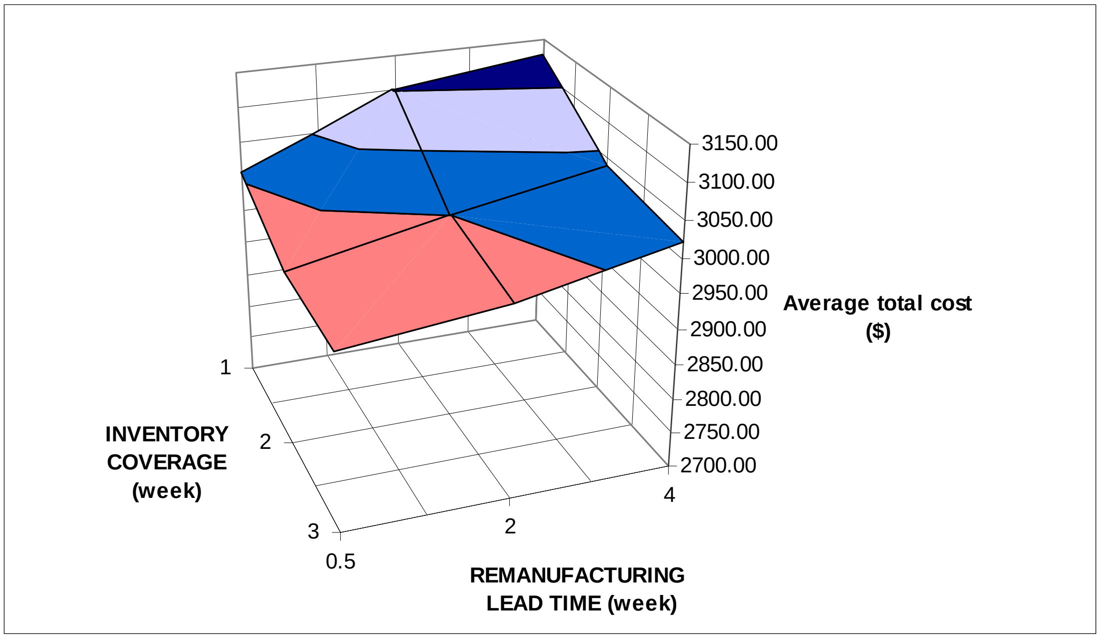


Figure 5.22: Evolution of the average total cost changing IC and RLT, PLT = 4

5.5 Case Study

In order to assess the findings and observations obtained through the simulation analysis a case study regarding a company involved in remanufacturing process was adopted in this research. Moreover, through this case study we were able to test the robustness of the developed generic model, and specifically its behaviour given realistic data for particularly exogenous variables. The company employed as a case study is CEVA Logistics. Data were obtained through interviews with company management and direct observation of the reverse supply chain process in which the company is involved. Information regarding the reverse supply chain process was previously outlined in Section 3.5.2. However, some of the data and information on company strategies are not used in the case study in order to observe the company's privacy policy.

5.5.1 CEVA Logistics

According to CEVA Logistics managers, the quantity of returns in the recoverable inventory is a fundamental element of ensuring the economic benefits of the remanufacturing process, in order to achieve an economy of scale, optimisation in remanufacturing capacity and transport cost optimisation. For example, only when the recoverable inventory reaches a level for which full pallets of returns can be assembled, particularly for the electronic components, are these sent to the remanufacturing centres. This policy is adopted in order to optimise transport costs and remanufacturing capacity. Moreover, another important factor to consider is the variability in the remanufacturing lead time among the different kinds of returns. For example, the lead time for mobile phones can often be days, even weeks for emergency temporary phones. However, as the company does not keep track of the remanufacturing lead times, no policies or strategies are applied in relation to the remanufacturing lead time to improve the cost benefits of the process.

The collected data concerned the quantity of customer orders and customer returns for several Telstra products handled by CEVA Logistics. However, as much of these data are aggregated for different kinds of products and the different Australian states of provenance, the analysis focused on a particular product (emergency temporary phones) for which orders and returns originate from Western Australia (WA). This choice was deemed suitable for the simulation model as it is based on a single product remanufacturing system. Moreover, the quantity of orders and returns for this state (WA) are suitable for the total system capacity applied previously in the simulation of the model. Under these conditions, the data collection was conducted through direct observation of the number of orders and returns for 60 consecutive weeks. These data were extrapolated from the company database, which holds general information for each transaction, including the product identification by name, the week number, the transaction (order or return), and the state of provenance. The collected and extrapolated data used for the analysis are shown in Table B.1 of Appendix B and relate only to emergency temporary phones.

Once these two time series data were obtained, the quantity of orders and returns for 60 weeks were used in the simulation model. For this purpose, two lookup functions were introduced into the model in order to formulate the exogenous variables *demand* (*demand* = *orders*) and the new exogenous variable *returns*. Indeed, the latter, in this case, is not formulated through the *sales*, since real data are available. However, the real returns collected during these 60 weeks came from previous company sales. The two variables are thus formulated as:

$$demand\ (t) = demand\ lookup\ (Time) \tag{38}$$

$$returns\ (t) = returns\ lookup\ (Time) \tag{39}$$

The factors *demand lookup* and *returns lookup*, which are not reported due to their length, are represented graphically in Figure 5.23.

The simulation analysis with real data focused on the effects of different capacity levels and different remanufacturing lead times for push and pull remanufacturing policies on the same measure of performance previously employed in Section 5.4. The value of the parameters and operational costs are equal to those used for the simulation of scenarios developed in Section 5.4.3. By this means, it was possible to compare the results between the two simulation analyses in order to assess the research findings and the robustness of the model.

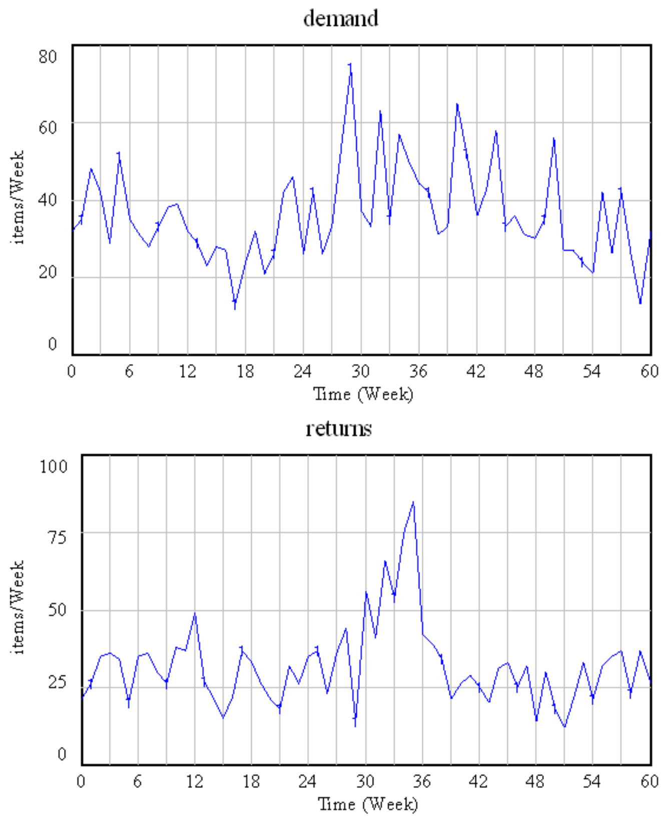


Figure 5.23: Customer demand and returns: real company data

Figure 5.24 (a) and Table 5.14 show the evolution of the average total cost and the numerical results for the simulation with real data, changing the capacity levels. The small Figure 5.24 (b) is a replica of Figure 5.18 and represents the same evolution for the simulation model.

Table 5.14: Average total cost using real data for different capacity levels, RE Ca = 60%

TOTAL REMANUFACTURING AND PRODUCTION CAPACITY	**10**	**30**	**50**	**70**	**90**
INVENTORY COVERAGE					
1	$5071	$4243	$3625	$3276	$3176
2	$5071	$4213	$3442	$3085	$2811
3	$5071	$4213	$3421	$3091	$2956

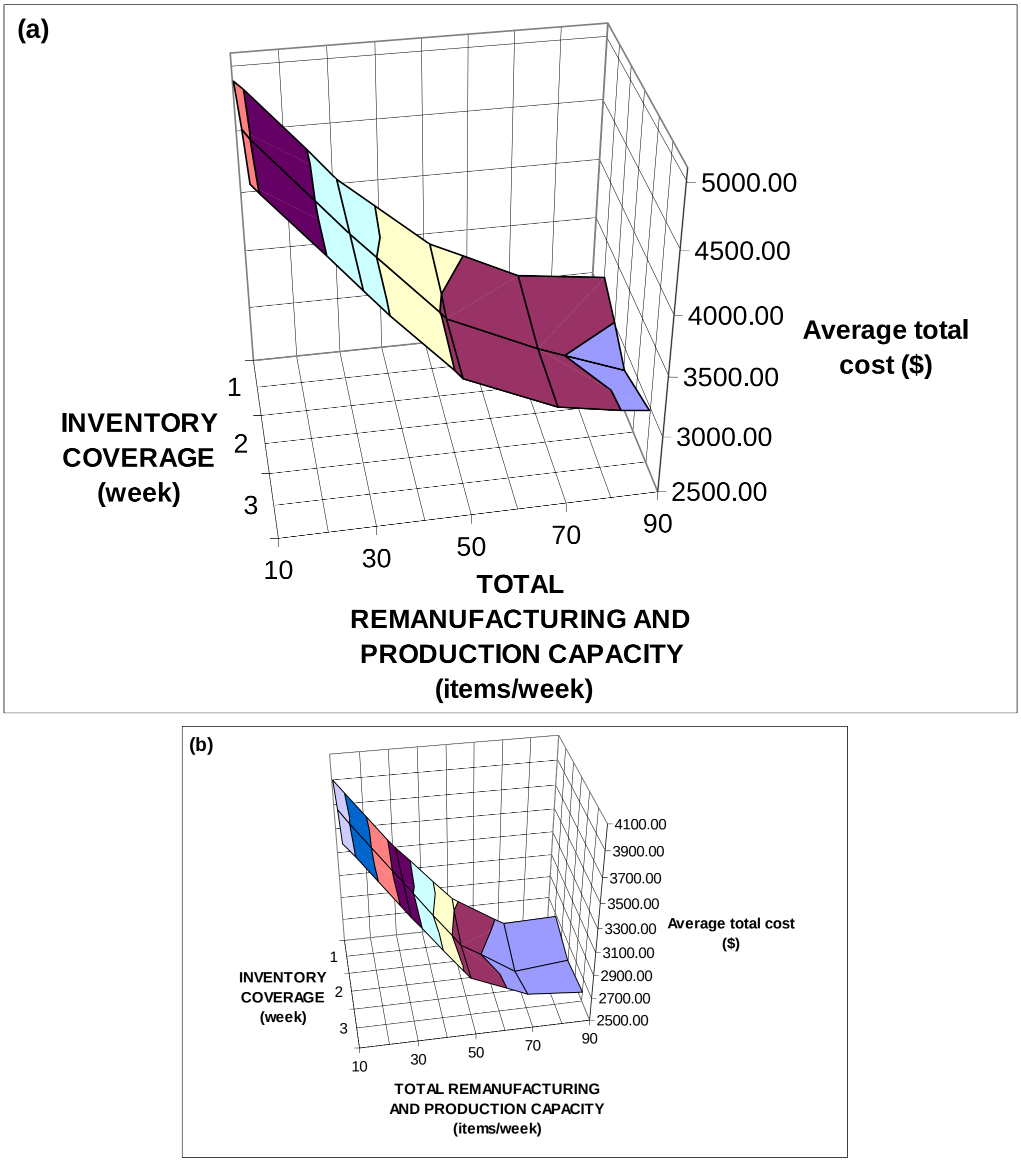


Figure 5.24: Evolution of the average total cost using different capacity levels, RE Ca = 60%

The similarity in the trend component between the two surface charts (a) and (b), which are also similarly not monotonic for higher values of total capacity (70 and 90) and monotonic for the lower ones (30 and 10), sheds light on the validity of simulation findings and the observations noticed in Section 5.4.3. Specifically, the model reproduces the same behaviour pattern given real input data. A more detailed analysis could be undertaken through a *behaviour reproduction test* (Sterman 2000) between real values and simulated output of the average total cost. This could compute point by point some measure of the error (e.g. Mean Absolute Error (MAE), Coefficient of determination, Mean Square Error (MSE), Mean Absolute Percentage Error (MAPE)) between the real data series and the model output. However, the absence of real total cost data in this research due to the company's privacy policy did not allow the development of such an analysis.

Similar observations were found regarding the simulation analysis with real data, this time changing the remanufacturing lead time. In this case, Figure 5.25 (a) and Table 5.15 represent the evolution of the average total cost and the numerical results for the simulation using real data. The small Figure 5.25 (b) is a replication of Figure 5.21 which represents the same evolution for the simulation model.

Table 5.15 Average total cost using real data for different remanufacturing lead times, PLT = 0.5

REMANUFACTURING LEAD TIME	**0.5**	**2**	**4**
INVENTORY COVERAGE			
1	$3090	$3092	$3296
2	$2885	$2910	$2994
3	$2938	$3062	$3102

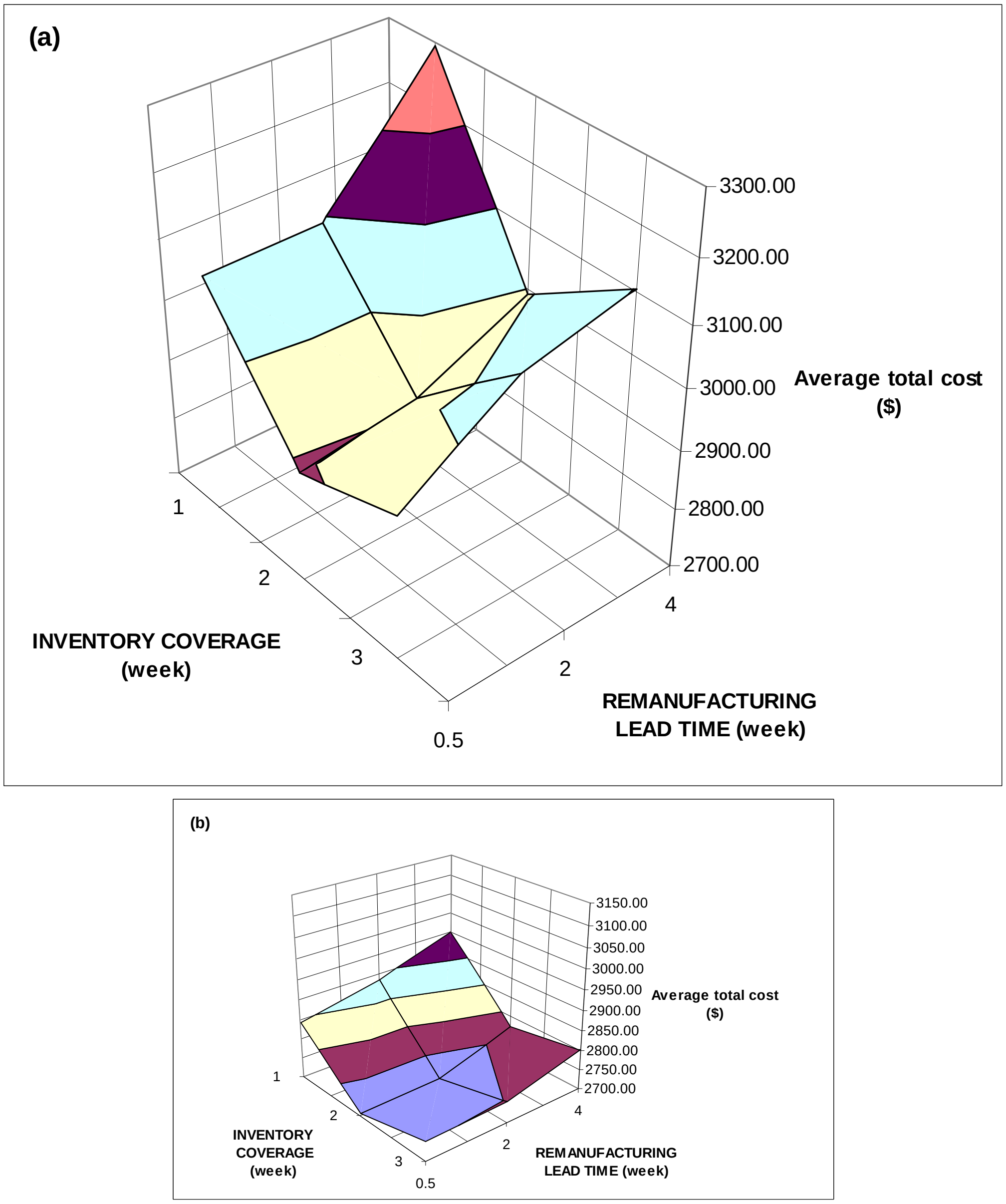


Figure 5.25: Evolution of the average total cost using different remanufacturing lead times, PLT = 0.5

5.6 Summary

In this chapter, a generic SD simulation model of a production and inventory system for remanufacturing was developed, focusing on the remanufacturing process. The objective was to explore and understand how the physical flow, the information flows and the company policies interact to generate the dynamics of the remanufacturing process. In particular, a joint capacity usage for the integrated remanufacturing and production activity and the respective lead times were introduced into the process. Moreover, backorder activity was considered and modelled in the system.

Similar to the process outlined in Chapter 4, through the SD simulation modelling process a CLD was developed to identify the variables involved, their interrelationships, and the main feedback loops. An SFD was then developed for which the relationships among the variables were formulated using mathematical equations. The obtained model was validated through a sensitivity analysis and a similar approach to the *behaviour pattern prediction testing* which involved the use of the case study presented in this chapter. Following the sensitivity analysis, the simulation of scenarios focused on various levels of particular parameters involved in the remanufacturing process: inventory coverage, total system capacity, remanufacturing capacity and remanufacturing/production lead times. Specifically, inventory coverage defines the use of pull and push inventory policies, while the system capacities and lead times defined the planned allocation of resources shared between the remanufacturing and production activities in order to use the cheaper remanufacturing as a substitute for the more expensive production activity where possible.

Several observations were made regarding the effects of changes in the total system capacity, remanufacturing capacity and remanufacturing/production lead times, considering different levels of inventory coverage. Such observations were obtained by analysing the total cost involved in the production, inventory, remanufacturing and backordering activities. In particular, it was observed that a reduction of total system capacity leads to a lower differentiation between the effects of adopting pull and push policies. Moreover, a higher capacity allocated to remanufacturing than to production activity leads to a quicker increase in the average total cost, suggesting an increase in the quantity of returns and a remanufacturing lead times reduction. Regarding the remanufacturing/production lead times, it was observed that for both pull and push policies a decrease of the remanufacturing lead time leads to a reduction in the total cost. Moreover, it was also observed that a larger increase in the total cost is generated by increasing the production lead time than an equivalent increase in the remanufacturing lead time. Some of these observations were assessed by analysing the related data for a case study company (CEVA Logistics) which is engaged in remanufacturing processes.

Chapter 6

CONCLUSION

6.1 Introduction

Production and inventory management is a fundamental activity within closed loop supply chain systems, particularly for remanufacturing processes. However, the integration between the reverse and the original supply chain leads to additional complexity in such systems in which control mechanisms and the planning of activities are required in order to achieve economic benefits. The challenge in evaluating and managing such complexity was the primary motivation of this research.

In this thesis, our main objective was to model the main factors that affect a production and inventory system in which production is integrated with the remanufacturing activity, and to investigate and evaluate effective control strategies for improving the performance of the system. To address this research objective, we developed SD simulation models of a generic production and inventory system for remanufacturing within the context of closed loop supply chains, focusing on the returns and remanufacturing processes. We also employed real data and information collected from companies that have adopted reverse logistics/closed loop supply chains and engaged in remanufacturing activities in order to assess the research findings obtained from the simulation analysis and to further validate the developed models of the production and inventory system for remanufacturing.

6.2 Thesis Summary

System dynamics simulation models of a production and inventory system for remanufacturing within the context of closed loop supply chains were developed in this research, focusing on the returns and remanufacturing processes of the system. The models developed present a comprehensive description and analysis of the system operations, taking into account important factors such as residence time, company service agreement with customers, customer behaviour, inventory coverage, integrated remanufacturing/production capacity and remanufacturing/production lead times. The models were used to enhance understanding of the dynamic interaction of these important factors affecting the behaviour of the system and to investigate and evaluate management strategies and related issues in the reverse supply chain.

Due to the complexity of the system, a divide-and-conquer approach was used to model and analyse the two sub-processes (returns and remanufacturing processes) independently. However, the two sub-models complement each other as they derive from the same system for which the assumptions were relaxed. For both SD models, the influence factors and their interrelationships representing the structure of the system were developed based on theoretical information obtained from the literature review and based on discussions with company management involved in remanufacturing activity. The latter were useful to gain a better insight into the world of reverse supply chain management not available in the literature.

After identifying the production and inventory system for remanufacturing, and the assumptions and policies to be modelled and analysed, we focused on the returns process.

The objective was to identify the influence factors and their interrelationships in a process in which the returns rate affects the dynamic behaviour of the system. In particular, our model was designed to address the issue of the uncertainty in the quantity and timing of returns, which negatively affects production/remanufacturing and inventory planning activity. Specifically, the returns rate was modelled by incorporating such uncertainty through the inclusion of the important factors of residence time, company service agreement with customer, and customer behaviour. The modelling and simulation processes followed the main steps of the SD approach. The CLD and SFD were developed in order to represent the qualitative and quantitative aspects of the model through a detailed explanation of the feedback structures and mathematical formulations that correspond to the relationships among the system variables and the system policies considered. We validated the model using a direct structure test (extreme condition tests) and a structure-oriented behaviour test (sensitivity analysis). Therefore, the model was simulated in order to analyse various scenarios based on the effect that the three important factors previously mentioned have on the system, using the average total inventory cost as the measure of performance. The results and observations obtained from the simulation of scenarios were assessed against data and information collected from two companies involved in reverse supply chain and remanufacturing (the Australian Mobile Telecommunications Association and Fuji Xerox Australia).

The same production and inventory system for remanufacturing was modelled and simulated focusing the analysis on the remanufacturing process. Specifically, we recognised the need to relax some of the assumptions previously considered for the analysis of the returns process in order to model and analyse the remanufacturing process by considering particular influence factors such as: integrated remanufacturing/production capacity, lead times, backorders and inventory coverage. The objective was to investigate and evaluate pull and push inventory policies for the integrated production and remanufacturing system in which shared resources affect capacity and lead times planning. Similarly to the returns process, the SD modelling approach involved the development of the CLD and SFD to represent different feedback structures and mathematical formulations. Moreover, the model was validated using a sensitivity analysis and a similar approach to the *pattern prediction testing* (Barlas 1989). The simulation analysis involved scenarios based on various values of inventory coverage, allocated total system capacity, allocated remanufacturing capacity and production/remanufacturing lead times. The simulation results and observations were assessed and analysed using real data obtained from a new company case study: CEVA Logistics. Such data relating to this company's remanufacturing process were also used to test the robustness of the model behaviour.

6.3 Research Findings and Contributions Revisited

As stated in Section 6.1, the primary objective of this research was to model the main factors that impact on a production and inventory system for remanufacturing within the context of closed loop supply chains, and to evaluate effective control strategies aimed at improving system performance.

The structure of the developed models and the simulation results achieved the main research objective. Specifically, the returns process was modelled using specific factors such as service agreement with customers, customer behaviour and residence time which affect the behaviour of the production and inventory system for remanufacturing. The modelled returns process can be linked to specific product categories using the knowledge of the distinctive element for a particular product, which in this case was the average residence time. The latter characterises different types of product depending on their variable time of use and recovery time, which in turn affects the system through the timing of returns. The service agreement with customers can affect customer behaviour in relation to returning used products, and can consequently affect the quantity of returns within the system. The variability of customer behaviour, which generates uncertainty in the quantity of returns within the system, has been modelled and analysed through three different customer behaviour patterns. Our contribution in this area is to extend current research with an approach to product recovery in which the correlation between demand and returns is obtained through the use of these particular factors.

On the basis of the simulation analysis focusing on the returns process, we concluded that efficiency in managing inventory, obtained through an increase in the quantity of remanufacturable returns which in turn increases the possibility of prompt remanufacturing as a substitute for costly production activity, can be achieved through shorter residence time, an increased level of company incentives and higher levels of positive responses from customers to these incentives. We also concluded that the uncertainty in the returns rate can be significantly reduced by increasing company incentives or the service agreement with customers which in turn increases the likelihood that customers will return used products. This can improve control of the returns rate and the total inventory costs. Our contribution in this area is to offer observations regarding efficiency in managing inventory activities for this particular system as well as to provide guidelines for determining the quantity and timing of used products returned by customers in order to reduce the uncertainty surrounding the timing and quantity of returns.

In terms of the remanufacturing process the main factors considered were inventory coverage, total system capacity and the remanufacturing and production lead times. These factors affect the process through the remanufacturing and production planning, which in turn affects the remanufacturing/production quantity and timing and the inventory levels within the production and inventory system for remanufacturing. Inventory coverage was used as the driving factor to investigate the pull and push policies in the system. Changes in its value lead the combined remanufacturing and production activities either to be closer to a pull strategy through the adoption of make-to-order behaviour or closer to a push strategy through the use of make-to-stock behaviour. However, these were not the only policies modelled in the remanufacturing process. Between the two stages of returns collection and storage of the recoverable inventory, the policy to inspect and store as recoverable inventory only the required and necessary quantity of returns was modelled by including the interrelationships among the variables involved. Similarly, in relation to remanufacturing activity the policy of producing a remanufacturing batch only when the recoverable inventory reaches an upper stock level was modelled in order to represent a pull policy between the recoverable inventory and remanufacturing. In this regard, it was found that CEVA Logistics's company policy of trying to optimise transport costs and remanufacturing capacity was represented by this model. Moreover, the policy of prioritising the cheaper remanufacturing over the more expensive production activity was modelled factoring in the relationship between remanufacturing and production orders. Through the simulation analysis, we concluded that the total system cost involving production, inventory, remanufacturing and backordering activities increases more quickly if a higher capacity is allocated to remanufacturing than to production activity. This result suggests that an increase in the quantity of remanufacturable returns and a remanufacturing lead times reduction will enhance efficiency in the remanufacturing process with higher remanufacturing capacity. We also concluded that a reduction of the total system cost can be obtained by decreasing the remanufacturing lead time in the case of both pull and push policies. Moreover, an increase in the production lead time increases the costs more than an equivalent increase in the remanufacturing lead time. Our contribution in this area is to provide an analysis of the effects on the system of these factors and policies modelled within the remanufacturing process, which might inform a strategic decision-making tool for production/remanufacturing and inventory planning activities.

6.4 Limitations of the Research

The research described in this thesis has a number of limitations that should be considered when making any generalisations about its findings. While a generic production and inventory system for remanufacturing was modelled and simulated based on a large set of possible products and industry, we supported the research findings by employing case studies of companies mainly involved in the consumer electronics industry. Consequently, the comparison between the research findings and the "remanufacturing real world" could be limited to this particular industry. Despite this limitation, our work and considerations can be applied and generalised to different products and industries as the main factors of the system influencing the research findings can be associated with a range of remanufacturable products.

Since our models of the production and inventory system for remanufacturing were modelled mainly based on theoretical information, we designed them without considering several important operations management activities related to a real remanufacturing company system. For example, the models did not involve purchasing, distribution or transport activities, collection and inspection network design, or product disassembly/assembly activities. Such particular features of a real system can interfere with the research findings, adding new operating costs and product characteristics that must be considered. However, although the models do not reflect a real remanufacturing system overall, we believe that they still reflect the main production and inventory management features integrated within a remanufacturing and returns process. Moreover, our main interest in this research was focused on production and inventory management and we believe that the addition of the other activities, which may be better analysed within distinct research areas, would have increased the complexity of the system and its analysis.

We are also aware that the research findings obtained through the simulation analysis and based on the evaluations of the effective control strategies did not consider the possible increase of company costs due to the implementation of such strategies. For example, regarding the returns process, we did not consider any possible increase in company costs resulting from an increase in company incentives or service agreement with customers. Similarly, for the remanufacturing process we did not consider any possible increase in the cost due to a reduction of the remanufacturing lead time. However, we believe that the objective of the research was more about an evaluation rather than implementation of the strategies, and that the operating costs considered for the measures of performance reflected the main production and inventory management costs.

6.5 Suggestions for Future Research

The research described in this thesis dealt with a series of issues relevant to the field of reverse supply chains and in particular closed loop supply chains. However, we believe that there is further scope for other lines of enquiry, which might be considered by future researchers. With the intention of further developing knowledge in this field, several challenging issues for further research projects to address are identified and proposed below:

- The findings of this research were obtained through the modelling and simulation of a generic production and inventory system for remanufacturing which is generally in line with those used in previous studies. In order to simplify the analysis and interpretation of such a system, a number of assumptions were made, some of which were relaxed to model the dynamic behaviour of the remanufacturing process. However, an opportunity for further research lies in the evaluation of system performance by relaxing the remaining assumptions. This could be achieved by remodelling the feedback structure of the system and incorporating the factors and their influence relationships that affect the system activities/processes.

  For example, the returns process was modelled without considering how uncontrollable disposal might affect system performance. Specifically, although it was considered a factor (*SERVICE AGREEMENT WITH CUSTOMER*) concerning the incentives that companies offer to stimulate the return process and avoid uncontrollable disposal, we believe that the latter can affect the quantity of returns, which in turn affects system performance. Therefore, a potential area for future research lies in improving the feedback structure of the model by incorporating those social and economic factors that through their influence relationships generate uncontrollable disposal in the returns process.

- Improving the model structure and its applicability in the real world might also be achieved through an extension of the meaning of the existing factors rather than by only relaxing the system assumptions. Specifically, several exogenous factors such as service agreement with customers, customer behaviour, residence time, inventory coverage, lead times and total system capacity were defined in a generic way without considering their social, economic or management backgrounds. An exploration of the origins and roles of these factors could expand the models to cover new areas of research focusing on different fields of study.

  For example, in the returns process the factors residence time and service agreement with customers can be connected with perspectives from the social, legislative and marketing disciplines. Similarly, in the remanufacturing process, the planning and right choice of the inventory coverage, system capacity allocation and lead times result from several operations and supply chain management considerations. Therefore, this research could be the starting point for further research aimed at analysing the impact that such disciplinary perspectives and considerations may have on a reverse supply chain system.

- The development of a remanufacturing system may be aimed at achieving economic benefits as well as environmental and sustainability benefits. However, in this research we focused the research findings only on the possible economic benefits of using production/remanufacturing and posited inventory costs as the measure of performance. Therefore, another opportunity for future work would be to investigate the impact that such models have on the environmental and sustainability goals and strategies of a company. It would be interesting to transfer the ideas applied in this research to the study of environmental and sustainability issues.

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Appendix A

Models Variables

A.1 Model Variables Focusing on Returns Process

Table A.1 lists the variables used for the modelling of the production and inventory system with remanufacturing focusing the analysis on the returns process. It provides a description and, the type and unit characteristic for each of them.

Table A.1: Model variables used in returns process modelling

Description	**Type**	**Unit**
Collected Returns	stock	items
Recoverable Inventory	stock	items
Serviceable Inventory	stock	items
Used Products	stock	items
Returns Accumulation	stock	items
collection	flow	items/month
failed returns	flow	items/month
accepted returns	flow	items/month
remanufacturing	flow	items/month

Table A.1 – continued from previous page

production	flow	items/month
demand	flow	items/month
demand inflow	flow	items/month
returns	flow	items/month
returns inflow	flow	items/month
PERCENTAGE DISPOSED	constant	dimensionless
INSPECTION TIME	constant	month
LOW LEVEL OF SERVICEABLE FOR REMANUFACTURING	constant	items
REMANUFACTURE UP TO LEVEL	constant	items
LOW LEVEL OF SERVICEABLE FOR PRODUCTION	constant	items
PRODUCTION UP TO LEVEL	constant	items
REPLENISHMENT FREQUENCY	constant	month
returns rate	converter	dimensionless
RETURN TIME	constant	month
return index	converter	dimensionless
RESIDENCE TIME	constant	month
CUSTOMER BEHAVIOUR	constant	dimensionless
SERVICE AGREEMENT WITH CUSTOMER	constant	dimensionless
DEMAND LOOKUP	lookup	items/month

A.2 Model Variables Focusing on Remanufacturing Process

Table A.2 lists the variables used for the modelling of the production and inventory system with remanufacturing focusing the analysis on the remanufacturing process. It provides a description and, the type and unit characteristic for each of them.

Table A.2: Model variables used in remanufacturing process modelling

Description	Type	Unit
Collected Returns	stock	items
Recoverable Inventory	stock	items
Serviceable Inventory	stock	items
Accumulated Orders	stock	items
failed returns	flow	items/week
accepted returns	flow	items/week
remanufacturing	flow	items/week
production	flow	items/week
orders	flow	items/week
fulfilled orders	flow	items/week
returns	flow	items/week
sales	flow	items/week
PERCENTAGE DISPOSED	constant	dimensionless
INSPECTION TIME	constant	week
expected accepted returns	converter	items
upper recoverable inventory stock level	converter	items
gap current recoverable	converter	items
REVIEW STOCK LEVEL	constant	week
remanufacturing capacity	converter	items/week

Table A.2 – continued from previous page

REMANUFACTURING CAPACITY REQUIRED	constant	dimensionless
TOTAL REMANUFACTURING AND PRODUCTION CAPACITY	constant	items/week
production capacity	converter	items/week
remanufacturing order	converter	items/week
REMANUFACTURING LEAD TIME	constant	week
production order	converter	items/week
PRODUCTION LEAD TIME	constant	week
gap serviceable inventory	converter	items/week
product allocation	converter	items
ALLOCATION TIME	constant	week
TIME TO ADJUST SERVICEABLE INVENTORY	constant	week
desired serviceable inventory	converter	items
INVENTORY COVERAGE	constant	week
DELIVERY TIME	constant	week
demand	converter	items/week

Appendix B

Data Collection

Table B.1 shows the orders and returns quantities of the emergency temporary phones collected from CEVA Logistics on a time horizon of 60 weeks and across different Australian states.

Table B.1: Data collection from CEVA Logistics

Week	Report	NSW	QLD	SA	VIC	WA	TOTAL
	0 order	90	144	41	48	32	355
	0 return	53	43	17	56	21	190
	1 order	105	123	43	82	35	388
	1 return	101	117	69	85	26	398
	2 order	121	170	37	96	48	472
	2 return	72	154	21	48	35	330
	3 order	113	145	35	68	42	403
	3 return	73	139	34	50	26	322
	4 order	71	79	43	82	29	304
	4 return	38	130	26	54	34	282
	5 order	102	194	57	98	51	502
	5 return	80	107	22	74	20	303
	6 order	91	247	57	119	35	549
	6 return	87	174	27	76	35	399
	7 order	140	178	37	197	31	583
	7 return	111	119	33	88	36	387
	8 order	100	199	40	78	28	445
	8 return	109	113	34	69	30	355
	9 order	96	191	49	89	33	458
	9 return	90	137	43	76	26	372
	10 order	107	120	28	97	38	390
	10 return	115	97	18	96	38	364
	11 order	87	169	59	94	39	448
	11 return	107	152	40	84	37	420
	12 order	103	177	47	71	32	430
	12 return	104	113	44	102	49	412
	13 order	140	97	52	75	29	393
	13 return	108	118	45	102	27	400
	14 order	92	193	42	91	23	441
	14 return	83	84	36	43	21	267
	15 order	89	140	44	56	28	357
	15 return	46	94	25	102	15	282
	16 order	107	164	49	81	27	428
	16 return	99	116	42	58	22	337
	17 order	69	171	44	78	13	375
	17 return	94	136	32	75	37	374
	18 order	111	109	39	76	24	359
	18 return	68	113	32	56	33	302
	19 order	109	133	39	76	32	389
	19 return	96	164	34	92	26	412
	20 order	87	177	57	73	21	415
	20 return	72	90	30	88	21	301
	21 order	115	106	51	89	26	387
	21 return	68	105	34	59	18	284
	22 order	94	158	56	88	42	438
	22 return	90	86	23	60	32	291
	23 order	69	101	32	86	46	334
	23 return	47	67	18	36	26	194
	24 order	89	135	51	51	26	352
	24 return	102	82	33	80	35	332
	25 order	92	125	33	64	42	356
	25 return	95	180	41	60	37	413
	26 order	74	122	30	84	26	336
	26 return	101	100	40	55	23	319
	27 order	93	122	42	75	33	365
	27 return	66	119	52	49	36	322
	28 order	95	88	84	77	54	398
	28 return	88	146	49	99	44	426
	29 order	58	220	52	60	74	464
	29 return	58	61	54	66	14	253
	30 order	81	78	48	73	37	317
	30 return	85	110	57	66	56	374

Table B.1 – continued from previous page

Week	Report	NSW	QLD	SA	VIC	WA	TOTAL
	31 order	61	121	42	109	33	366
	31 return	33	68	56	63	41	261
	32 order	172	88	48	108	63	479
	32 return	108	151	19	86	66	430
	33 order	103	93	29	95	35	355
	33 return	132	118	39	67	54	410
	34 order	109	82	34	107	57	389
	34 return	97	105	16	56	75	349
	35 order	109	81	22	85	50	347
	35 return	154	121	41	66	85	467
	36 order	115	115	24	93	44	391
	36 return	81	99	28	105	42	355
	37 order	110	113	29	85	42	379
	37 return	89	122	17	68	39	335
	38 order	155	93	45	80	31	404
	38 return	77	110	17	62	34	300
	39 order	89	79	32	82	33	315
	39 return	108	133	28	64	21	354
	40 order	142	80	25	76	65	388
	40 return	76	89	13	38	26	242
	41 order	81	96	29	78	52	336
	41 return	75	99	25	47	29	275
	42 order	86	87	28	87	36	324
	42 return	70	96	22	44	25	257
	43 order	91	76	33	75	43	318
	43 return	48	86	19	52	20	225
	44 order	112	81	24	89	58	364
	44 return	58	85	21	58	31	253
	45 order	82	134	50	86	33	385
	45 return	66	97	12	67	33	275

Week	Report	NSW	QLD	SA	VIC	WA	TOTAL
	46 order	141	208	97	126	36	608
	46 return	60	71	18	18	25	192
	47 order	169	171	49	120	31	540
	47 return	76	95	17	65	32	285
	48 order	157	121	61	105	30	474
	48 return	65	110	24	66	14	279
	49 order	135	153	42	121	35	486
	49 return	68	108	31	53	30	290
	50 order	141	129	100	171	56	597
	50 return	80	91	46	58	18	293
	51 order	54	114	24	43	27	262
	51 return	47	127	14	38	12	238
	52 order	107	164	49	81	27	428
	52 return	99	116	42	58	22	337
	53 order	111	109	39	76	24	359
	53 return	68	113	32	56	33	302
	54 order	87	177	57	73	21	415
	54 return	72	90	30	88	21	301
	55 order	94	158	56	88	42	438
	55 return	90	86	23	60	32	291
	56 order	89	135	51	51	26	352
	56 return	102	82	33	80	35	332
	57 order	92	125	33	64	42	356
	57 return	95	180	41	60	37	413
	58 order	74	122	30	84	26	336
	58 return	101	100	40	55	23	319
	59 order	69	171	44	78	13	375
	59 return	94	136	32	75	37	374
	60 order	109	133	39	76	32	389
	60 return	96	164	34	92	26	412