Forecasting Product Returns

and

Their Impact on Dynamic Performance in Closed-Loop Supply Chains

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A thesis submitted in partial fulfilment of

the requirements of the University of Greenwich

for the Degree of Doctor of Philosophy

August 2016

DECLARATION

I certify that this work has not been accepted in substance for any degree, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy being studied at the University of Greenwich. I also declare that this work is the result of my own investigations except where otherwise identified by references and that I have not plagiarised the work of others.

ACKNOWLEDGEMENTS

I would like to extend my thanks to Dr. Li Zhou for her help throughout this research. Her guidance has been invaluable and her support truly made this thesis possible.

ABSTRCT

With the current attention on ecological and environmental protection, regulations on environmental protection and extended producers responsibilities, more and more manufacturers are introducing reverse logistics (RL) into their forward supply chain (SC). RL together with forward logistics consists of a closed-loop supply chain (CLSC). This research aims to establish a systematic understanding of RL systems with a focus on product returns and their impacts on CLSC operations.

In order to do so, the research is developed from both theoretical and practical angles. In terms of theoretical understanding, the research studies up-to-date literature regarding RL and CLSC, and identifies criteria affecting RL and CLSC operations specifically in product returns. Then, the mathematical models are developed based on practical RL and CLSC operations including examining existing regulations and their impact on customer product return behaviour, mapping RL operations and forecasting product returns, and exploring the CLSC dynamic performance.

The research contributes to both current study on RL/CLSC and practitioners within the relevant areas as: (1) it explores various RL options and their practices in a CLSC system through a comprehensive literature review, which builds a foundation for mapping RL operational processes, developing mathematical models in understanding the impact of legislation on RL, forecasting product returns, and exploring CLSC dynamic performance; (2) it quantifies relationships between legislative enforcement, green awareness and product returns over a product life cycle; (3) it advances a generic Graphical Evaluation and Review Technique model with a control theory method, i.e. Mason's rules to forecast multi-level product returns; (4) it develops a SD model to examine how product returns affect the CLSC's product order rate and its inventory level, both are directly related to cost.

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Abbreviations

3P	Third party
APIOBPCS	Automatic pipeline, inventory and order based production control system
APVIOBPCS	Automatic pipeline, variable inventory and order based production control system
B2B	Business-to-business
B2C	Business-to-customer
BOM	Bill of Material
CDF	Cumulative distribution function
CPF	Cumulative probability function
CLSC	Closed-loop supply chain
CSR	Corporate social responsibility
EEP	Electric and electronic products
EOL	End-of-life
EPR	Extended producers responsibilities
FCPN	Fuzzy coloured Peri net
GDM	Grey decision making
GM	Grey model
GERT	Graphical evaluation and review technique
GRA	Grey relational analysis
GST	Grey systems theory
IOBPCS	Inventory and order based production control system
MGF	Moment-Generating Function
MIP	Mixed Integer Programming
MINLP	Mixed Integer non-Linear Programming
MILP	Mixed Integer Linear Programming
MRR	Manufacturer-retailer-recycler
OEM	Original equipment manufacturer

PBB	Polybrominate biphenyl
PBDEs	Polybrominated diphenyl ethers
PDF	Probability density function
PERT	Project evaluation review techniques
PLC	Product life cycle
PRR	Product return and remanufacturing
RL	Reverse logistics
RoHS	Restriction of hazardous substances
SC	Supply chain
SCM	Supply chain management
SD	System dynamics
SEPA	State Environmental Protection Administration
SI	Serviceable inventory
SMILP	Stochastic mixed integer linear programming
VIOBPCS	Variable inventory and order based production control system
WEEE	Waste electrical and electronic equipment
WIP	Work-in-progress

INTRODUCTION

Chapter 1. Introduction

In this chapter, a general background of the research is introduced, the current status of the Chinese electronics industry including current relevant legislation is discussed. EU legislation and regulation is also reviewed as it can be seen as a benchmark of the Chinese legislation, and the legislation is further discussed in Chapter 4. Research aims and objectives are determined by research gaps. Finally, in this chapter the thesis structure is drawn to outline the research.

1.1 Research background and motivation

With the current attention on ecological and environmental protection, regulations on environmental protection and extended producers responsibilities (EPR), more and more manufacturers are introducing reverse logistics (RL) into their forward supply chain (SC) (Zhang et al., 2008). RL together with forward logistics consists of a closed-loop supply chain (CLSC) as shown in Figure 1.

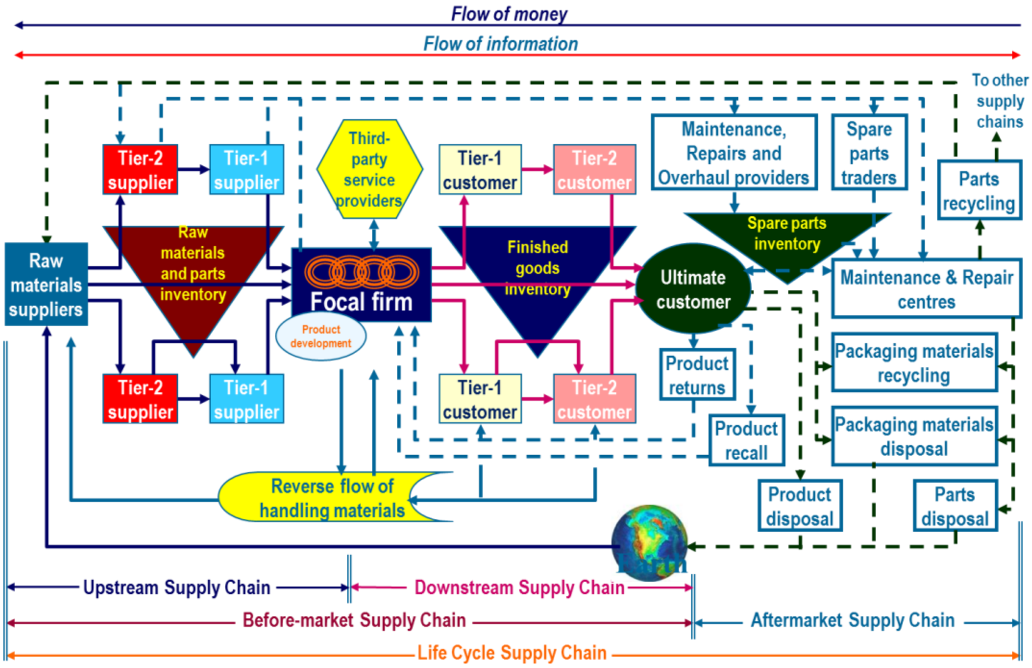


Figure 1. A closed-loop supply chain (Okongwu, 2005)

The forward SC starts from the acquisition of raw materials which may be exploited from the earth. The raw materials are transferred into components, parts and half-finished products through various tiers of suppliers. The final products are assembled at the focal firm, i.e. a manufacturer in this study. The finished products are delivered to customers. The tier 1 customers refer to distributors and tier 2 refers to wholesalers. The inventories in the forward supply chain serve as a buffer against uncertainties. The RL starts from when the products are sold to the terminal customers. It includes: product return with retrievable value; product recall; product maintenance incurred and parts and packaging materials recycling.

Originally, issues including green logistics and reverse logistics arose from public awareness towards environmental concerns (discussed by Dowlatshahi, 2000). As government gradually became involved in legislation towards end-of-life (EOL) products, it plays a crucial role in terms of regulating and enforcing the activities within a closed-loop supply chain, such as collecting, sorting, reproducing, demolishing, etc. Reverse logistics refers to the movement of the goods from a consumer towards a producer in a channel of distribution (Murphy, 1986). In 2001, Fleischmann (2001, pp.5) developed the definition of reverse logistics as "the process of planning, implementing and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain directions for recovering value and proper disposal". RL is often considered to be a more uncertain and complex process than a forward SC (Dowlatshahi, 2000). The uncertainties and complications are mainly from product return behaviour, i.e. it is hard to predict return quality, quantity and timing. Therefore, it is extremely challenging when managing a CLSC.

On one hand, managing RL operations has been proven to be challenging due to uncertainties. The uncertain factors (both external and internal) give rise to manufacturers having more difficulty in operating RL compared to their forward SC. Specifically, strategic decision-making must consider uncertainty from all sources. Within literature forward SC management has been thoroughly examined and evaluated, but the process of RL has been less discussed (Mohammed & Walid, 2012).

On the other hand, there is no doubt that highly effective and feasible RL can bring direct economic profit, including reduction of resource, inventory and distribution costs (Wei et al., 2015). RL programs in addition to the various environmental and cost benefits can proactively minimise the threat of government regulation and can improve the corporate image of companies (Carter & Ellram, 1998). Furthermore, it can also bring new competitive advantages to manufacturers, e.g. improving customers' satisfaction, a closer customer relationship, consistent with environmental regulations, etc. With more and more countries signing off WEEE-like legislation, more and more CLSC entities see RL as a revenue opportunity (Guide & Van Wassenhove, 2009).

1.2 An example of RL system: Electronic products recycling in China

In this section, China's electronic product recycling system is used as an example to demonstrate a RL system and its operations. It covers the regulation and end user aspects respectively. The purpose is to provide a practical foundation and verification for the mathematical models that this thesis has developed later.

China has been one of the major global electronic manufacturing centres over a few decades (Zhu & Liu, 2010). Due to its large population and the electronic goods consumption in China, the electronic wastes generated annually are gigantic. However, RL of the Chinese electronic industry is still at its preliminary phase. Based on the data revealed by the Ministry of Environmental Protection of the People's Republic of China, in the first two quarters of the year of 2015, about 24.8 million TV sets, more than 1.2 million refrigerators, more than 2.5

million washing machines, 25 thousand air conditioners and more than 4.5 million personal computers were recycled properly by authorised recycling companies (http://recycle.cheaa.com/2016/0629/482210.shtml, access 06-July-2016), compared to the sales data that more than 20 million refrigerators, more than 17 million washing machines and about 38.5 million air conditioners were sold only in the first quarter of the year of 2015 (http://www.cheaa.org/contents/116/3742.html, access 06-July-2016). On the other hand, China suffers from environmental and ecological dual pressures, as well as scarcity of natural resources (Zhu & Liu, 2010). This has led to the Chinese government promoting a series of regulations/laws dedicated to its sustainable economy (Zhu & Liu, 2010). However, the success of these efforts remains debatable and myopic in many aspects.

1.2.1 A review of EU legislation related to electronic products

It is necessary to review the EU legislation towards electric and electronic products (EEP), due to the fact that Chinese legislation and regulation is related to, and has a similar structure, as it is trying to reflect and respond to the relevant EU laws. The Waste Electrical and Electronic Equipment Directive (WEEE Directive) is one of these regulations, which has been amended several times, the most recent update being carried out in 2012. The WEEE Directive sets collection, recycling and recovery targets for all types of electrical products. For products produced after 2005, the arrangements for collection and recycling of waste electronic products place the responsibility onto producers and distributors. It has set clearly defined targets which currently stands at 45% of the weight of products entering the market. The aim by 2016 is to raise this rate to 85%.

The directive on the Restriction of Hazardous Substances in electrical and electronic equipment (RoHS) came into force in 2003, and has become law in all the EU member states. It restricts the use of hazardous materials in electronic products. The regulation applies to manufacturers, importers and distributors, and places responsibilities with them, such as, in the event of non-compliance, manufacturers have to inform the market, and distributors must recall the products.

1.2.2 A review of Chinese legislation related to electronic products

Similarly to the EU WEEE Directive and the RoHS, Management Regulations on the Recycling and Disposal of Waste Electronic and Electrical Products and Measures for the Control of Pollution from Electronic Information Products are the equivalent legislations currently enforced in China. They are broadly similar, i.e. the overall recycling target is 70% contrasting to 85% in EU. There are the six substances which are restricted in electronic products i.e. lead, mercury, cadmium, hexavalent chromium, polybrominate biphenyl (PBB) and polybrominated diphenyl ethers(PBDEs).

Outside of these two regulations, Household Electronic Products Trade-in Methods published in 2010 is another related regulation, which specifies the trade-in (subsidy) standards of common household electronic products when they are returned by customers. By 2013, 630 million Yuan had been spent on authorised recycling. However, the result of it is not as successful as planned, as mentioned before in this chapter, compared to the sales figure, only a fraction of these products had been properly recycled (http://www.cheaa.org/contents/116/3762.html, access 06-July-2016).

1.2.3 Current legislation and regulation related to the Chinese household electronic industry

Currently, there is no legislation specifically relating to household electronic product return in China. However, several pieces of legislation have covered household electronic products to some extent. In this section, legislation related to household electronic products are categorised into two main types, i.e. legislation and regulation related to resources, legislation and regulation related to product return.

1.2.3.1 Legislation and regulation related to raw materials

Poison and hazardous materials have been banned or limited in usage. These restricted raw materials include lead, mercury, cadmium, hexavalent chromium, PBB and PBDE. Also, all component parts which contain the above raw materials are subject to the same restrictions. Furthermore, regulations and legislations are there to encourage usage of renewable resources, for instance, 'Announcement regarding VAT Policies for Renewable Resources' published in 2008, subsidises renewable resources recycling companies through a VAT refund process. In July 2015, a renewed version of this announcement has been published. It includes more types of renewable resources eligible to be refunded and an instant VAT refund procedure, e.g. used cables, used aluminium cans, etc.

1.2.3.2 Legislation and regulation related to waste products

Almost all the current regulations stem from the EU's RoHS directive. In August 2003, State Environmental Protection Administration (SEPA) published 'Announcement regarding environmental management of waste electric and electronic equipment'. It addressed any waste including the above materials which are hazardous wastes, detailing they must be collected, stored and handled by licensed collectors.

In terms of renewable resources, several regulations have been published to encourage their usage. In August 2005, SEPA published 'Technical specifications of pollution control for processing waste electrical and electronic product (HJ/T 181-2005)’. It regulates waste EEPs' handling and management.

1.2.4 Public awareness towards environmental protection

Waste EEP which are used for industrial purposes have been widely accepted as being potentially hazardous to the environment. However, waste household EEP are always seen as 'valuable' rather than 'dangerous' by the public. Nevertheless, several surveys have shown that if a 'greener' product causes an extra cost, most people would not be happy to pay for it unless they have no other choice. Current public awareness can be improved by (Zhu & Liu, 2010):

(1) Education. Public awareness can be improved through intensive education and broadcasting. The Chinese public already has a knowledge of environmental protection, but a lack of knowledge regarding practical methods. The public has had awareness regarding daily-basic environmental issues, i.e. hygiene and atmospheric pollution, but had less awareness regarding ecology. This is because hygiene and atmospheric pollution can be immediately and easily identified by the public, e.g. atmospheric pollution causing breathing difficulties. It is more difficult to identify ecological and environmental issues as the impact may not be immediately apparent, e.g. invisible heavy metal accumulation in fish stocks.

(2) Encouragement. The public needs to be encouraged to actively hand in their EOL EEP properly. Legislative enforcement can only be treated as an initial method. It needs to be accompanied by other methods to improve public awareness which would result in a positive handling reaction. Methods include economic subsidy and proactive recycling channels. Without these actions, there is little incentive for customers to dispose of their EEP responsibly rather than in the most convenient way.

1.2.5 Current electric and electronic products recycling and handling

Based on the research on the Chinese electronic industry (Zhu & Liu, 2010; Lau & Wang, 2009), China's electronic RL still remains at its preliminary phase. The features of these stages can be shown in the following ways:

- most of the manufacturers currently in the market have no ability to operate complex RL channels;
- informal recycling is largely active;
- customers lack of common environmental protective awareness;
- legislation is ineffectively enforced on both manufacturers and consumers.

Current waste EEP return is through the following four channels:

(1) Customers return EOL products back through recycling bins set up by authorised recyclers;

(2) Customers return EOL products back through recycling spots set up by authorised recyclers;

(3) Scrap-men collect from customers;

(4) Scavengers collect from dumping.

In 2015, 85.86% of waste household EEP were collected by scrap-men. Some of them were returned to an authorised channel, but most of them were disposed of randomly (http://recycle.cheaa.com/2016/0719/484263.shtml., accessed 08-Aug-2016). Scrap-men can travel/be present in all places, their collection is not easily monitored, but they are flexible and collect door to door, which means authorised recyclers cannot collect as much as them. After collection, most of the waste is transferred to unauthorised recyclers.

In terms of waste handling, most of the EOL EEP are handled by unauthorised recyclers. This type of primitive handling of EOL products includes:

(1) Sorting out reusable EOL products from the returned products, simply refurbish or fix them, then resell them as second-hand products.

(2) For non-reusable products, dismantling is applied. For instance, motors, compressors, tires, etc. are usually retrieved from a used car, and resold as second-hand parts.

(3) Valuable metals, such as copper, gold, etc. are retrieved from the non-usable parts. However, this process is often applied by unprofessional workers. They have limited knowledge and awareness of environmental protection and are often profit-orientated. For instance, recovering copper from electric wires and electric cables through an incineration method; retrieving gold from circuit boards by immersing them into an acid solution and tipping waste into the environment directly.

(4) Disposing of non-retrievable parts into environment directly without necessary detoxification.

Besides the above primitive handling methods, almost all of these unauthorised recyclers deal with the wastes in an illegal manner, i.e. in an informal workshop without necessary equipment to prevent further environmental contamination; under no or limited supervision by professionals, potentially causing a further contamination and hazard to the immediate environment and workers. Guiyu in Guangdong Province and Wenling in Zhejiang Province are two examples of primitive waste handling centres.

Compared to those unauthorised primitive waste handling businesses, authorised and technically advanced recyclers are experiencing operational difficulties, due to inflexible collection channels. For example, Jin Ze Recycling Co. (Nanjing) is the first state-run electric and electronic waste handling centre. However, it was forced to be temporarily halted only a few hours after it opened due to a lack of return products to be handled. Other authorised recyclers, such as the professional recycling centre set up in Zhejiang Province and the recycling alliance between Hisense, Haier and Aucma are experiencing the same dilemma as Jin Ze, due to a similar reason.

In conclusion, current handling and management of waste EEP is still very primitive and lacks monitoring. It features:

(1) Multiple management. Current management towards waste EEP belongs to multiple departments, e.g. ministries of resources, trade, environmental protection, information, etc.

(2) Low efficiency. There is not a unified waste EEP recycling channel. Private waste recycling channels have low efficiency and potential hazards towards the environment.

(3) High risk. Most of the waste handling aims towards resale as second-hand products through a quick refurbishment. These second-hand products may contaminate the environment and bring new problems.

1.3 The significance of the research

1.3.1 The research gaps

The literature review chapter will reveal the detail of up-to-date studies on RL/CLSC. Within this section, the following research gaps are briefly highlighted:

(1) Uncertainties within a CLSC/RL system need to be identified. A good understanding of the uncertainties enables managing such a complex system in a comprehensive way. Kiff et al, (1998) claim that customers do expect and require the availability of a service and repair network "just in case". Forward logistics flow starts from suppliers, but reverse logistics flow starts from customers. Customer behaviour is more random than suppliers. Pochampally and Gupta (2004) reported that the success of a prospective reverse supply chain depends heavily on participation of three important groups, customers, local government officials, and supply chain executives. The customer perspective can be seen from following two aspects: perspective towards the EOL products and perspective towards take-back products. The former means how customers deal with their EOL products, which includes disposal frequency, disposal methods, disposal cost, disposal volume and product types. A

research study conducted on the logistics service providers in Singapore found the voice of customer as the most important driver of the logistics management (Sum & Tao, 1999). The latter means how customers expect reverse logistics service. However, as a main factor, customer return behaviour still lacks comprehensive study.

(2) Conceptual models developed for the study of CLSC/RL have been mainly focused on operations management such as inventory, cost, system dynamics (SD) performance, and others. There is little research on how legislative enforcement impacts on customer behaviours when returning products.

(3) Despite of the importance of forecasting in operations management, research on product return forecasting is scarce due to the complexity of CLSC and the uncertainties in RL.

(4) The impact of product returns on SD performance has not been well explored. Understanding of SD is crucial for managers when planning production schedules and allocating resource. It is directly related to cost, profit, lead time management and customer satisfaction.

1.3.2 The logic of research framework in this study

The case of China's recycling system suggests the key elements in a RL system, that is: legislative enforcement, manufacturing and remanufacturing operations, supplier cooperation, and customer environmental awareness. These elements and their interrelationship will be addressed in this thesis respectively, and based on the research gaps identified above, the structural development of this research can be clarified:

- It starts by investigating how legislation impacts on customer return. Product return is the trigger of RL. The amount of product returns influences on the profitability of RL; and how the quality of returns affects RL operations decisions: resale, refurbish, repair, dismantle, recycling and dispose. The study of legislation shall provide an overview of how government involvement can promote RL practice.

- It then develops an algorithm on how to predict product returns based on the RL process and product structure. Forecasting is vitally important in RL and CLSC. The result of forecasting provides an instruction for manufacturers and remanufacturers on resource planning, production and remanufacturing schedule, purchasing decisions, and many other decisions. Nevertheless, while many approaches have been developed in forecasting customer demand there is little research on predicting product returns due to the uncertainties and complexity of RL.

- Finally, it explores how product returns impact on system dynamic performance when RL is integrated in a forward SC. It adopts system thinking and system dynamics (SD) approaches to map the CLSC process, the input and output of each stage in the process, and the operational performance measurements. It focuses on the impact on dynamic performance of uncertainties in the return yield, RL lead time and the product consumption lead time. Two outcomes are studied: order rate and serviceable inventory with a unit step input and a random input respectively.

1.3.3 The potential theoretical and practical contributions of this research

The research contributes to both current study on RL/CLSC and practitioners within the relevant areas as:

- Exploring various RL options and their practices in RL system through a comprehensive literature review, which builds a foundation for mapping RL operational processes, developing mathematical models in understanding the impact of legislation on RL, forecasting product returns, and exploring CLSC dynamic performance;

- Quantifying relationship of legislative enforcement, green awareness and product returns over a product life cycle (PLC);

- Advancing a generic Graphical Evaluation and Review Technique (GERT) model with a control theory method, i.e. Mason's rules to forecast multi-level product returns;

- Developing a SD model to examine how product returns affect the CLSC's product order rate and its inventory level, both are directly related to cost.

1.4 Research aims and objectives

1.4.1 Research aims

This research aims to establish a systematic understanding of RL systems with a focus on product returns and their impacts on CLSC operations.

In order to do so, the research is developed from both theoretical and practical angles. In terms of theoretical understanding, the research studies up-to-date literature regarding RL and CLSC, and identifies criteria affecting RL and CLSC operations specifically in product returns. Then, the mathematical models are developed based on practical RL and CLSC operations including examining existing regulations and their impact on customer product return behaviour, mapping RL operations and forecasting product returns, and exploring the CLSC dynamic performance.

In each of the models, managerial insights have been provided, which would be useful to manufacturers, remanufactures and policy makers.

1.4.2 Research objectives

In order to address the research aim the following research objectives have been formulated:

O1: Identifying key factors and key phases within RL operations (Chapter 2);

O2: Examining impacts of legislative enforcement and green awareness towards product returns over a PLC (Chapter 4);

O3: Justifying and adopting an appropriate method that can forecast multi-level product returns in a stochastic RL system (Chapter 5);

O4: Examining the impacts of product returns on SD performance in a CLSC (Chapter 6).

1.5 The thesis structure

The thesis structure intends to achieve the specified research objectives in a logical and academic manner as shown below:

A literature review is first conducted and research gaps concerning the research objectives are identified. Research methodology plays a critical role to ensure the rigorousness and reliability of the research results. Research, academic and logic justification relies on a thorough understanding of ontology and epistemology. Through studies on current research methodologies related to RL and CLSC, the research methodologies have been developed to achieve the research objectives, including secondary documentary study, i.e. literature review, mathematic modelling, GERT and SD modelling. Each of the above tries to achieve one of the research objectives. The thesis structure is mapped out in Figure 2. It shows an overview of the research perspective and process.

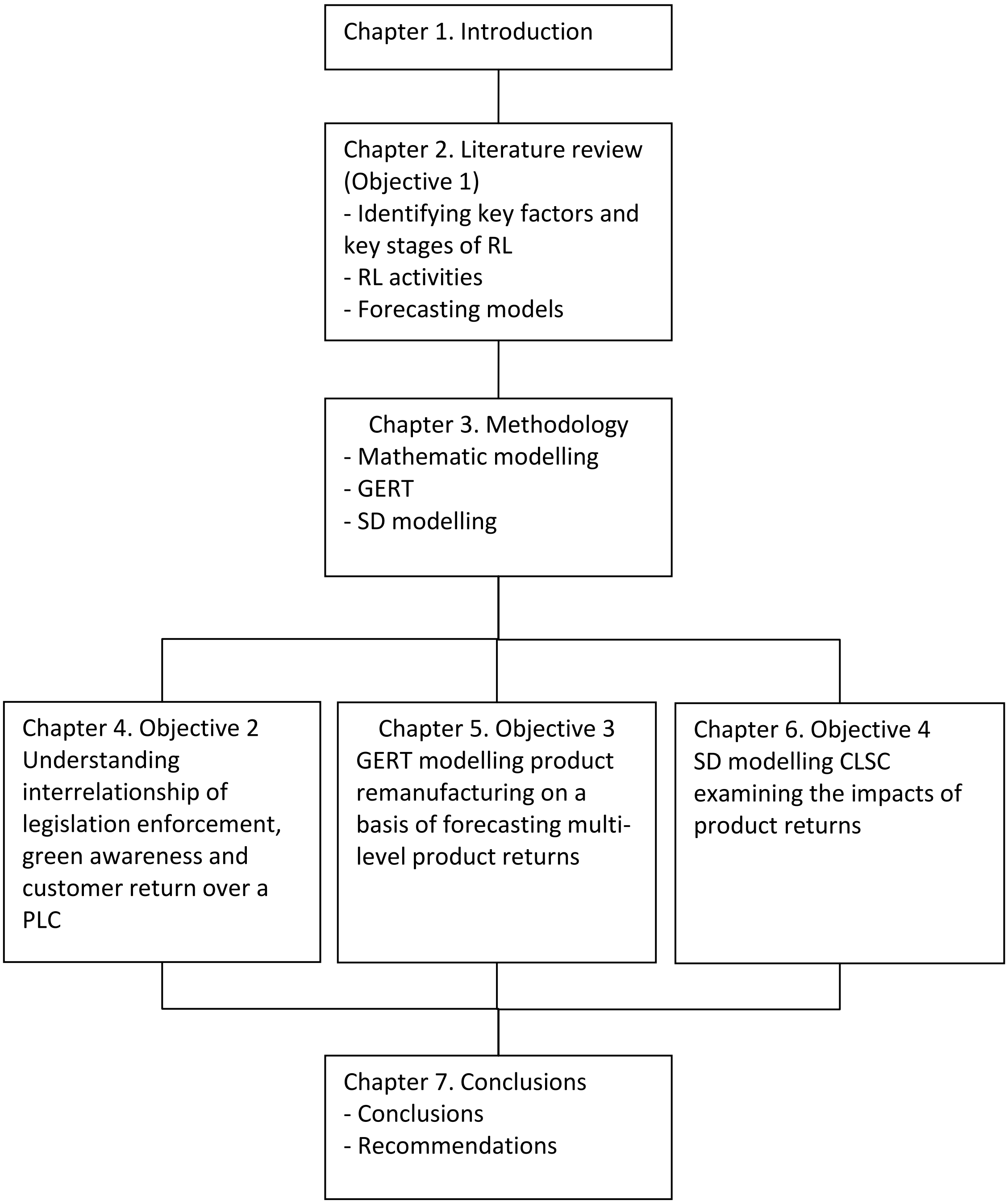


Figure 2. The thesis structure

LITERATURE REVIEW

Chapter 2. Literature review

2.1 Introduction

It has been widely accepted that a systematic overview of the existing knowledge is the key to improving and developing research in related areas (Saunders et al., 2009; Seuring & Müller 2008; Govindan et.al., 2014). Since RL and CLSC research has been conducted over two decades, many authors have proposed different approaches trying to solve various issues within it, e.g. quantitative modelling tends to solve the difficulties in the field of planning and controlling, qualitative research tends to understand the root and causes of relevant issues (Tiben-Lembke & Rogers, 2002; Verstrepen et al., 2007; Zhou et.al, 2016). This literature review provides an overview of current CLSC research focusing on product returns. It starts from addressing conceptual issues related to the topic, then through a review of relevant theoretical development, sustainable dimensions, RL activities in the returning process are identified. Quantitative research on product return issues within the field of RL/CLSC is also reviewed.

The purposes of this chapter are: to identify the research gaps therefore to verify the contribution of the thesis; to classify the uncertainties in RL/CLSC which will achieve the research objective 1.

2.2 Definitions

To prepare the groundwork for the subsequent literature review, key terms related to this thesis are defined. A complete CLSC contains two parts: a forward supply chain and a backward supply chain. A forward supply chain 'encompasses all activities associated with the flow and transformation of goods from raw materials stage (extraction), through to the end user, as well as the associated information flows' (Seuring & Müller, 2008, pp. 1700). A backward supply chain, which can be interchanged with reverse SC or RL, defines a supply chain that is redesigned to efficiently manage the flow of products or parts destined for remanufacturing, recycling, or disposal and to effectively utilize resources (Dowlatshahi, 2000). The European Working Group on RL, REVLOG (Dekker et al., 2004), puts forward the following definition of RL:

> *The process of planning, implementing and controlling backward flows of raw materials, in process inventory, packaging, and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal.*

A multiplicity of classifications exists in terms of recovery operations within product recovery management, i.e. resale, reuse, refurbish, repair, dismantle, recycling and disposal (Tibben-Lembke & Rogers, 2002). From the perspective of whether the physical form of an object is retained, Horneber (1995), for example, mentioned two recovery goals: regaining the work piece and regaining the material based on his/her classification. According to this, reusing means remanufacturing an item for its initial purpose; recycling, on the other hand, is to regain the material and utilise it for its initial or a different purpose.

With the increasing significance of product take-back legislation, the issue of how to retrieve the used products arises. The two most common ways of defining RL differ in one key-aspect. Either RL is seen as a pure process of physically moving goods and products in reverse to the conventional flow of materials and products (Bayles, 2001), or, RL encompasses “green” operations such as material or waste reduction (Kopicki et al., 1993).

It also needs to be noticed that RL is different from a sustainable supply chain. The latter has a broader content as it may include the forward chain. In fact, a RL chain is only a part of a sustainable supply chain, which is managed in a way 'to meet the needs of the present without compromising the ability of future generations to meet their own needs' (Brundland, 1998). As RL focuses on value recovery and recovered value entering a new SC, RL is also different from a green supply chain, which concentrates mainly on environmental and ecological issues in a SC. And finally, RL is a part of a complete CLSC. The latter emphasises the importance of coordinating the forward with the reverse streams.

2.3 Reverse logistics process and activities

2.3.1 RL operations

The following researchers have dealt with various issues within RL operations, and a great deal of literature has been found which focuses upon the theoretic aspect or framework of RL operations. Additionally, different aspects of RL processes have been discussed by various authors within their works. Fleischmann et al. (2000) drew a 'framework reverse distribution', which can be seen as one of the early illustrations of a RL flow. It integrates a forward distribution flow which is from producer to user with a reverse distribution flow which is from user to producer. In fact, later illustrations by other researchers are mainly based on Fleischmann's framework with some adjustments added on this simple version. For instance, Krumwiede and Sheu (2002) reviewed industrial practice and added transportation companies as a third-party provider in a reverse distribution channel.

Inventory plays an important role in a CLSC system, as it is the input of a reverse operation. Chung and Wee (2008) presented a CLSC system which includes an inventory flow and has been adopted by other researchers. Beamon (1999) presented a generic form of CLSC, which extends a traditional forward chain to a 'semi-closed' chain that contains RL operations. Similarly, another generic CLSC is illustrated by Tonanont (2008). The significance of this generic form of supply chain is that it provides possible decisions, i.e. disposal, recovery and reuse as raw materials, for manufacturers or distributors, once returned a decision can be made for this product from all possible decisions.

In general, participants which are contained within an integration of both forward and reverse supply chain largely depend on the type of RL operation. Three types of alternative RL operations have been designed. They are: 1) Direct RL; 2) 3rd party RL; 3) RL alliance.

- Direct RL

Direct RL means that original manufacturers are responsible for their own RL. The RL operations here include not only the wastes from the manufacturing process but also the EOL products, excess inventory, product recalls and unwanted or outdated products. For example, Xerox applies this alternative to recycle its EOL photocopy machines (Maslennikova & Foley, 2000). Besides investment in fixed assets and managerial expenses, direct RL requires manufacturers to invest much in the setting up of the reverse channel. This alternative mode applies to manufacturers who have proven distribution channels, or produce bulk products/high-value commodities, because these types of products tend to have a relatively simple and fixed logistic channel. There is relatively low transaction cost, because of no other party being involved in RL. However, the total cost of products has to include the RL cost, so it affects customers' demand, hence affects manufacturer's profits based on the supply-demand principle. Low demand leads to a low quantity of EOL products, hence the low profit from RL.

When other outside parties are involved in RL, the process is no longer seen as a manufacturers' own responsibility. Indirect RL have 2 different modes: 3rd party RL and RL alliance.

- Third party (3P) RL

Some products, such as batteries, need to be properly disposed of, but not all manufacturers have such ability. Lieb and Randall (1999) suggested that third-party executives viewed RL as an opportunity area and mentioned that RL activities performed by third-party providers may become more prevalent in future. Third party RL allows the original equipment manufacturer (OEM) the opportunity to focus on their core competencies, leaving the remanufacturing operations to the companies specialising in these functions (Ravi, 2005). The third party involved in the RL can provide professional service. The third party can be a pure RL service provider, or it can supply renewed products/raw material to customers/ manufacturers.

- RL alliance

Some previous research mentions logistics alliance as symbiotic logistics (Ravi, 2005). A logistics alliance consists of different independent manufacturers. The alliance takes charge of both forward and RL. Several manufacturers share the same channel, managerial and technical methods. It is also a "strategic alliance of two or more independent entities designed to provide the desired level of customer service in accordance with the concept of integrated logistics management" (Mitchell et al., 1993). Using a logistic alliance can help to mitigate a number of uncertainties of RL. It provides a more effective means for "combating the problems created by the need to maintain the reverse channel capability" (Ravi, 2005).

Figure 3 is the schematic diagram of RL alternatives where self-direct logistics and indirect logistics including 3P logistics and RL alliance are shown, developed from Thierry et al.'s (1995) integrated supply chain.

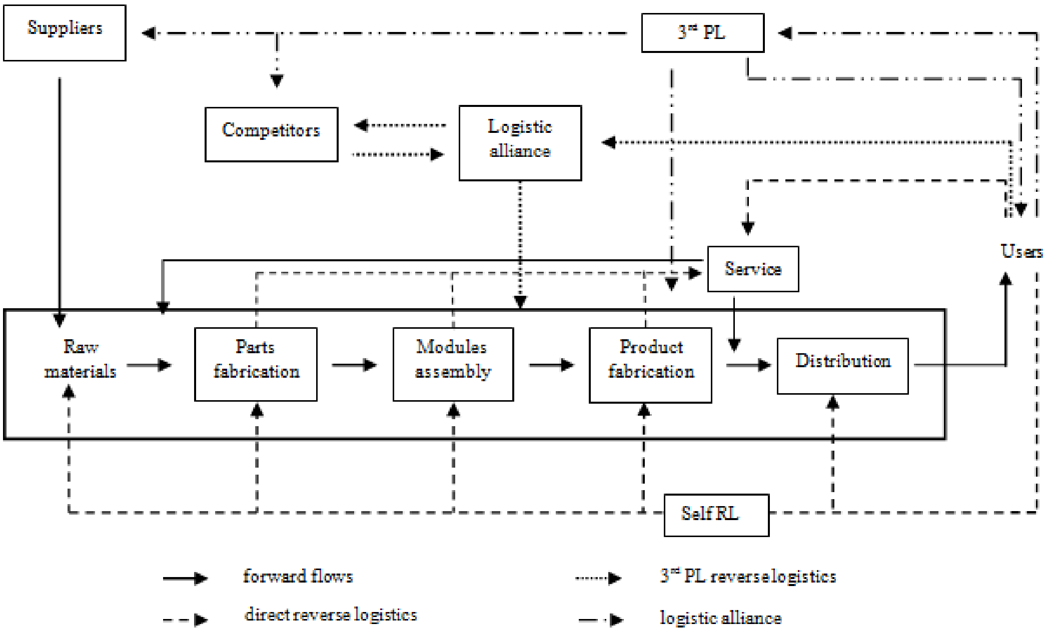


Figure 3. Alternative of RL operation (developed from Thierry et al. (1995))

2.3.2 RL activities

In terms of activities within RL operations, a RL process contains three main phases: returning, pre-recovery and recovery. Figure 4 demonstrates the RL process in dark lines. Returning refers to ① bringing the products from different stages of after sales to a point of recovery. Note, the point of recovery is a general term which can locate at a retailer, manufacturer, distributor, wholesaler and 3PL (Third party logistics). The return process can occur at any point of the forward SC. For instance, a customer can return unused products to the retailer. Depending on the quality, the unused products can be directly resold; or a malfunctioning product can be returned for repair or exchange; or a used product to a collection point; and product call-back from end user and unsold from wholesalers and distributors. Pre-recovery follows up the returning process, at this point the returned products are inspected then sorted according to their quality. Recovery occurs at a different level: ② resell, ③ remanufacturing ④ recycling. Finally, ⑤ if recovery is not possible, products are to be disposed.

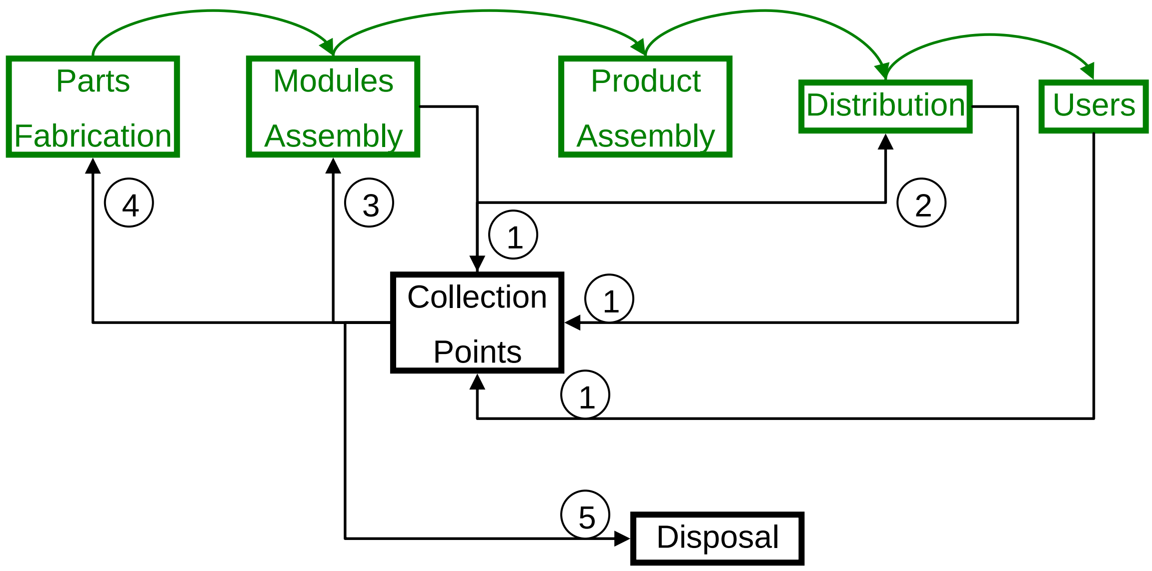


Figure 4. Process of RL

- Returning

RL starts from product return. Products which are returned or disposed of are either lacking some or all of their original functions are obsolete or no longer needed. According to Dekker et al. (2004), three types of return could happen within a supply chain, i.e. manufacturing returns, distribution returns and customer returns.

Table 1. Types of return (adopted from Dekker et al., 2004)

Types of Return	Definitions	Reasons
Manufacturing Returns	Components or products return due to various reasons in the production phase.	-Raw material surplus; -Quality-control returns; -Production leftovers/by products.
Distribution Returns	Returns that are initiated during the distribution	-Product recalls; -Business-to-business

	phase.	(B2B) commercial returns; -Stock adjustments; -Functional returns.
Customer Returns	Returns initiated once the product has at least reached the final customer.	-Business-to-customer (B2C) commercial returns; -Warranty returns; -Service returns; -End-of-use returns; -EOL returns.

Effective and efficient management of product returns is an important challenge arising in RL practice and research.

- Pre-recovery

When the returned products reach their collection points, they are inspected and sorted according to their initial quality. If the quality meets the resale or reuse standard, the returned products can be reused or redistributed immediately; or if they are found not to be worth salvaging, they are likely to be land filled. Otherwise, they are kept in the system for a further reprocessing (Dekker et al., 2004).

- Recovery

In terms of recovery, there are two types of recovery i.e. direct recovery/reusing and indirect recovery/reprocessing. In some research, recovery has been termed as product exchange (Das & Dutta, 2013).

Direct recovery/Reusing: If the quality of returned products is (close to) as-good-as-new, products can be fed into the market almost immediately through reuse. Reusing refers to remanufacturing of an item for its initial purpose. It contains direct reuse/resale and partial reuse. Products eligible for this classification must remain good quality. When a product has reached the end of its useful life it can be broken down into its subassemblies and original parts, some of which can be reused in the same form for the same use without remanufacture or repair. These will be put into inventory as spare parts and used in the repair process. Reuse may be considered as a form of source reduction. Indirect recovery/Reprocessing: If the quality of returned products cannot achieve the requirement of direct recovery, another type of recovery may be involved that now demands more action, i.e. a form of reprocessing.

- Remanufacturing

Remanufacturing is defined as the ‘upgrading’ of an EOL product into a product with an ‘as good as new’ condition. Remanufacturing as a product recovery operation is extensive and includes product disassembly, cleaning and identification of parts, parts recovery and product re-assembly. It contains repairing and refurbishing. Product remanufacture or refurbishment is not a new concept. Equipment that has been recovered in a usable condition but lacks current functionality can be remanufactured and stored in inventory for use quickly. The benefit is a recovered asset can often be remanufactured for a fraction of the cost of manufacturing a new one. For example, the photocopier manufacturer, Xerox, remanufactures “recovered equipment” to strict performance specification, it estimates that remanufacturing results in annual savings of USD 200 million and this can be a significant competitive advantage over competitors (Gattorna, 1998). The automotive sector is one of the first industries to practice remanufacturing, however, the historic rationale behind remanufacturing is manifold and does not originate from one particular source (Seitz, 2007). Only recently is remanufacturing gaining scientific significance in a variety of industry sectors, such as photocopier, cellular telephone and single-use camera remanufacturing.

Three main participants can be identified in the remanufacturing operation: customers, Original Equipment Manufacturer (OEM) and independent manufacturers. Apart from customers as a participant who return products back, OEM who undertakes remanufacturing operations is a participant in this process, too. The OEM can be either a manufacturer or a supplier of the original materials. Most commonly, the OEM collects the used products and distributes the remanufactured products through their own logistics channels (Margarete, 2007). Independent remanufacturers, who are not related to the production and distribution in any way, perform services for the OEM.

- Recycling

Differing from the goal of reusing which is to retain the identity and functionality of products. In recycling, the identity and functionality of products and components is lost. Products which are unsuitable for refurbishment, repair or resale can be broken down into their component parts and recycled into new materials. For example, composting organic material is a form of recycling. As Canon Incorporation does in its RL operations, it has switched to use pulp moulds made completely of recycled paper as shock-absorbing packaging material since 1991, and used recycled polystyrene foam for packing since 1998 (Mochizuki et al., 2001). The purpose of recycling is to reuse materials from used products and components. These materials can be reused in the production of original parts if the quality of materials is high, or else in the production of other parts.

Recycling begins when used products and components are disassembled into parts. These parts are separated into distinct material categories. These separated materials are subsequently reused in the production of new parts. Recycling is currently being applied to a number of used products. For example, virtually all metals in discarded cars (on average 75% of the weight of a car) are being recycled in western countries like Germany, the UK, and the United States (Thierry et al., 1995, pp. 120).

The above recovery options are summarised in Figure 5.

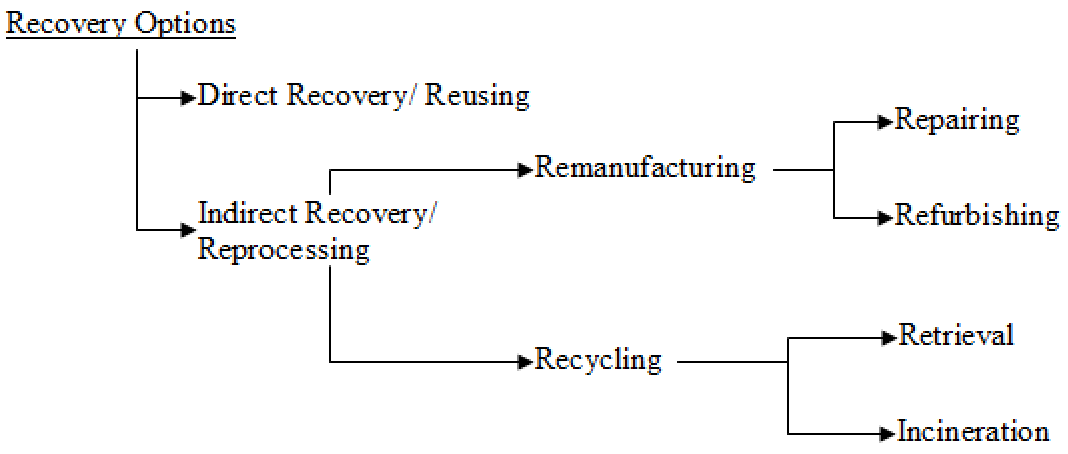


Figure 5. Product Recovery Options

2.4 Measuring sustainability of RL and CLSC

The reverse loop of a CLSC has always been seen as having an initial sustainable motivation. It is a widely accepted concept that *economic, environmental and social performance*s are three important aspects and measures in a CLSC (Dekker et al., 2004).

Sustainability dimensions relate to the driving forces behind RL operations. It has been pointed out by many authors that economic benefit has been widely accepted as the most important enabler and motivation for manufacturers to get involved in RL (Andel, 1997; Linton, 1999; Schendler, 2002; Seitz, 2007). Nevertheless, companies continually strive to achieve cost savings in their production processes (Ravi et al., 2005). This is because managing a RL chain is particularly challenging due to the uncertainties in RL. As mentioned before, these uncertainties are product return timing, quantities and quality. It makes remanufacturing planning difficult to undertake. In addition, the returned product quantity is normally small, making it hard to conduct mass-production, a costsaving production operation in general. The stochastic feature of a RL system also contributes to the complexity of system management. This includes, apart from the above mentioned three uncertainties, marketing perception and acceptance of remanufactured products; marketing price of raw materials affecting recycled materials; changing regulations and remanufacturing standards, etc. All of this adds extra ‘burden’ to manufacturers taking part in RL.

There are a variety of value recovery options available, depending on the type of product returned, its condition and its anticipated future demand (Visich et.al., 2007). Value recovery options include direct reuse, direct resale, repair, refurbishment, remanufacture, cannibalisation and recycling (Thierry et al., 1995; Dekker et al., 2004). However sometimes manufacturers have to invest much in RL before they get any economic benefit from it. Nevertheless, even with no clear or immediate expected profit, manufacturers would get (more) involved with RL because of marketing, competition, corporate social responsibility, and strategic development, from which there are expected indirect gains. Ravi et al. (2005) used the financial dimension to measure how the RL operations cater to the shareholders’ financial objectives. Stakeholders can have different objectives, besides profitability, some stakeholders look at corporate image as equally important as direct economic profits. RL activities can lead to an increased corporate image (Carter & Ellram, 1998). So how stakeholders balance tangible profit and intangible social impact, and how they measure economic incomes and corporative image drive RL decisions. In summary, direct economic benefits include: gains from cost reduction and value recovered; indirect economic benefits include: gains from anticipating or impeding legislation, market protection and improvement and green image.

RL is based around the reuse and conservation of materials and products, and this philosophy and goals mirrors the growing concern surrounding the environment, encouraging RL increasing implementation. Concern for environmental issues is proven to be one of the drivers of RL, as RL reduces negative impact on the earth and improves the corporate image of companies.

Marketing and promotion based around ecological and environmental themes has become a powerful tool for businesses. As the benefits of this strategy become apparent, manufacturers have begun to embrace further reuse, recycling and remanufacturing of their own products to ensure that the business is perceived as a "green business" (Thierry et al., 1995). A sincere and committed effort from top management is essential for successful deployment of RL programs (Carter & Ellram, 1998). However, green awareness varies among manufacturers, and it leads to different RL disposition and different performance.

Social dimension is often referred to as corporate social responsibility (CSR). As one of the earliest publications related to RL, Drumwright (1994) mentioned CSR from a consumer perspective. It can be seen as one of the earliest mentions of the social dimension. The customer perspective can be seen from the following two aspects: perspective towards the EOL products and perspective towards take-back products. The former means how customers deal with their EOL products, which includes disposal frequency, disposal methods, disposal cost, disposal volume and products type. A research study conducted on the logistics service providers in Singapore found the voice of customers as the most important driver of logistics management (Sum & Tao, 1999). The latter means how customers expect reverse logistics service. CSR concerns how the core company within a RL operation become responsible, and it focuses on the relationship between a business and its surrounding society, i.e. stakeholders, government, environment, etc.. In particular, this dimension is usually measured as peoples wellbeing and number of jobs generated from a sustainable business (Drumwright, 1994).

The sustainability and ecological performance of a company also depends on the suppliers (Godfrey, 1998). So many companies have started partnering and mentoring with their suppliers, such as providing guidance to set up an environmental management system to improve the operational efficiency (Hines & Johns, 2001). However, social issues are a factor which is rather difficult to be quantitatively measured (Seuring, 2013). To measure it, some researchers tend to quantify it as an environmental factor, for example, Cruz-Rivera and Ertel (2009) used the environmental variable (i.e. emissions) to set up a social responsibility dynamic model; some researchers tend to quantify it as a cost, for example, Hsueh and Chang (2008) consider CSR as a cost in their model. Although it has been pointed out social issues cannot be simplified as a single impact (Seuring & Müller, 2008; Seuring, 2013), to make quantitative modelling practical, it is necessary to focus more on the aspect of social issues, trying to quantify these, when setting up a model.

2.5 Identifying and analysing factors within RL operations

This section reviews research on RL operations. There are three main research types in the current literature: theory building, qualitative study, quantitative modelling and simulation. Theory building research tends to review existing literature and explain research issues of RL from a theoretical perspective. Most of this type of research set up a conceptual framework, which tries to virtually elaborate and lay the fundamentals of RL theory, e.g. Dekker et al. (2004). Qualitative study of RL focuses on a particular event. They identify and analyse the case proposed. General resolutions are often given to generalise the case study. This type of research often contributes both RL theory and application (Kumar & Yamaoka, 2007). Quantitative modelling and simulation occupy the largest proportion of RL research literature. Different quantitative methods have been attempted to solve various challenges within a RL process (Zhou et al., 2016).

This section reviews the first two types of research literature, i.e. theory building, qualitative study. Quantitative modelling and simulation, the research method adopted in this research, will be reviewed in Chapter 3 as part of the research methodology review.

2.5.1 Research of RL operations

Current studies towards RL operations contribute on both theoretical and practical perspectives. In terms of the former contribution, the following three aspects are covered by research.

2.5.1.1 Empirical studies of RL on a particular country and/or an industry

Empirical studies can be both quantitative (e.g. testing hypotheses through statistical analysing of survey) and qualitative (e.g. case studies, documentary analyses, etc.). Of all the literature selected to review by this research, 27 of them are empirical studies focusing on a particular country and/or an industry. Together they have drawn a picture of current RL status, in a real world background. The case studies cover a variety of industries, e.g. publishing, retail, fabric, etc. The first and oldest case study reviewed by this chapter, is Wu and Cheng's (2006). They studied key factors affecting RL on the Chinese publishing industry and suggested solutions to the problems. Verstrepen et al.'s (2007) case study investigated Flanders' RL operation, focusing on interrelationships among return reasons, recovery options, outsourcing, lifecycle length and value of products. Talbot et al. (2007) proposed an investigation on residual value extraction processes within small and medium enterprises within the electronics industry. Bernon and Cullen (2007) identified RL management methods in the UK retail sector, and suggested a framework which helps to manage customer returns. Kumar and Yamaoka (2007) investigated the relationships between reduction, reuse, and disposal in the Japanese car industry. Biehl et al. (2007) analysed the US carpet industry and presented a solution taking the impact of environmental factors into account in a RL system. Zhu et al. (2008) presented their findings of capabilities of Chinese organisations on the adoption of Green Supply Chain Management practices. In another of their studies (Zhu et al., 2008), they presented significant positive interrelationships between organisational learning, support, and the adoption of green supply chain management practices. Kumar and Putnam (2008) identified the primary forces for a CLSC across three industries (automotive, consumer appliances and electronic products). Lau and Wang (2009) selected four

Chinese electronic companies to study the motivations and barriers of RL operation behind them, further discussing the RL implementation in China. Geyer and Blass (2009) researched the UK's mobile phone industry, in terms of its collection, reusing and recycling status. The results of it show that the mobile phone reuse market is promising despite its low disposal rate. Mukherjee and Mondal (2009) studied an Indian photocopier remanufacturer to understand relationships among key issues pertaining to making decisions in the remanufacturing process. Muller and Thun (2010) empirically studied the German automotive industry from a practitioner's perspective. Erol et al. (2010) explored Malaysian business organisations' RL activities. They find economic benefits can be generated through waste reduction and better resource utilisation. Erol et al. (2010) studied the status of RL management within the Turkish automotive, white electronic goods, general electronic products and furniture industries. Grant and Banomyong (2010) qualitatively studied product recovery management of fast-moving consumer goods (single-use camera). Subramoniam et al. (2010) drew a framework which helps OEM suppliers to make strategic decisions for remanufactured products through an investigation of US and EU companies. Subramoniam et al. (2010) studied the automotive aftermarket from a strategic planning angle, and presented some propositions through their case study. González-Torre et al. (2010) studied the barriers which exist in Spanish automotive industry. They also studied whether internal or external barriers constitute a greater impediment for organisations seeking to implement environmentally oriented RL practices. Bo and Yamamoto (2010) compared and contrasted the characteristics of e-waste recycling systems. Matsumoto and Umeda (2011) researched Japanese companies' RL motives and incentives through a cross-industry survey. Abraham (2011) explored the apparel aftermarket in India from a strategic and operational perspective. Olugu and Wong (2012) developed an expert fuzzy rule-based system for CLSC performance evaluation in the automotive industry. Quariguasi Frota Neto and Van Wassenhove (2013) studied take-back initiatives of personal computers in Brazil. They found 'high collection costs, low residual values, tax and unclear and conflicting legislation' are the main reasons for discouragement of OEMs participation in take-back programmes. Ye et al. (2013) discussed the effects of three institutional pressures namely, government, customer and competitor, on

RL implementation within the Pearl River Delta in China. Halabi et al. (2013) presented a research approach of RL in Colombia, focusing on the plastic industry.

The above research contains studies from different perspective, i.e. different industries and countries. Although RL operation varies from one industry to another, the fundamental aspects within are similar across the industries. The empirical studies hence work as a solid theoretical research background of RL/CLSC study, in terms of operational decision-making assessment, appraisal criteria, etc. The results are adapted by this research in the later chapters.

2.5.1.2 Theoretical development of RL research

The review of theoretical development focuses on the legislative compliance and the interrelationships between key factors within RL operation.

Legislative pressures/incentives have been proven to be one of these key factors (which will be further addressed in Chapter 4). Legislation is always seen as an important driver of RL. Legislation refers to any jurisdiction that makes it mandatory for companies to recover its products or accept these back after the EOL of the product (Ravi et al., 2005). In European countries, RL is mainly driven by legislation (Srivastava and Rajiv, 2006). Some legislation is compulsory, and some legislation is only a guideline. For example, the EU WEEE directive is one of a series of 'producer responsibility' directives that makes EU OEMs pay for the recycling and/or safe treatment and disposal of the products they put on the market when they eventually come to be thrown away (Dekker et al., 2004). It also encourages a set of criteria for collection, treatment, and recovery of WEEE and makes producers responsible for financing these activities (WEEE, 2003). There has also been a restriction on the use of hazardous substances in production processes, which facilitates the dismantling, and recycling of waste electronics.

There has been extensive discussion throughout literature in terms of compliance with governmental regulations (Toffel, 2003). Neto et al. (2011) researched five items under the European Directive on WEEE and how to extend a CLSC system toward becoming a sustainable network. They argued that manufacturers' RL decisions should ensure compliance with existing legislation. For returns there are two major classifications for regulation: (1) Those involved with after sales product return, e.g. any product bought online within the UK can be returned up to 23 days after the original purchase; (2) Rules designed to protect the environment. An example of this is the restrictions on Hazardous Substances as laid down by the WEEE. The focus for the first category is upon return of unsatisfactory and faulty items, with the second addressing issues related to returns, both consumers and manufacturers of products with hazardous material content and/or products deemed not to meet the desired sustainability as detailed by WEEE.

Interrelationships between different RL participants have also been proved to be crucial. Channel relationship competence represents the manufacturers' abilities to work together with different parties within the logistic operation. In forward logistics, channels functions reflect the tasks required in moving a product through the channel of distribution from producer to end consumer (Nevins and Money, 2008). Strategic alliances in a channel are made with various members of supply chain as the companies are realising that the individual attempts at product reclamation make little sense both economically or environmentally (Cairncross, 1992). Existing research suggests that partnerships characterised by high levels of trust lead to stronger relationships with beneficial outcomes (Fukuyama, 1995). Some manufacturers tend to use current forward logistics channels as a basis to set up RL business. Having good channel relationship enables manufacturers to track and manage the flow of materials and information through a network of organisations, which contributes to the environmental sustainability and ecological performance of a company, because achieving these performances also depends on the suppliers (Godfrey, 1998). So many companies have started partnering and mentoring with their supplier, such as providing guidance to set up an environmental management system to improve the operational efficiency (Hines & Johns, 2001).

The vast majority of surveys have provided sufficient evidence that environmental and social concerns are the main factors affecting CLSC operations. Among the environmental related measures, energy demand (mostly fuel consumption of vehicles) and carbon-footprint (i.e. carbon dioxide emission) are commonly used as either decision variables or parameters. In the model of a household plastic waste recycling system (Bing et al. 2012), environmental issues have been considered from its economic impact as one of the input parameters to the model, in this case fuel consumption has been taken into account. In addition, CLSC and RL contributes to reducing environmental impact and hence can improve corporate image (Carter & Ellram, 1998).

A ‘green’ image of producing environmentally friendly products has become an important marketing element, which has stimulated a number of companies to explore options for take-back and recovery of their products (Thierry et al., 1997). Murphy et al. (1995) have found that 60% in a group of 133 managers surveyed considered the issue of the environment to be a very importance factor and 82% of them expected that the important would increase in the years to come. Here, green awareness refers to a general readiness for reverse logistics, or the psychological willingness of the manufacturers to introduce reverse logistics into their logistic operations. A sincere and committed effort from the top management is essential for successful deployment of reverse logistics programs (Carter & Ellram, 1998).

Technical factors consider the effort of technical development towards a CLSC. Technical support includes to what extent the current manufacturing means and products support future RL operations; to what extent the current technical staff can deal with RL; and the state of current production (i.e. production scale, annual production, production scheduling) as well as new technologies. Many companies have product development programs encompassing design for environment for product recovery through disassembly. The variable of technical skills is adopted from forward logistic measurement, especially in an internet-enabled business, where technical skills typically refer to the technical knowledge of and experience with IT applications (Bharadwaj, 2000; Mata et al., 1995). Within this dimension, production scale and production scheduling have been reflected in some quantitative models.

2.5.1.3 Measuring RL operation performance

RL decisions over different operational choices relies on performance appraisal. Through different modelling, RL performance is appraised, hence the decision is made.

Profitability is one of the key performance measurements which motivates various stakeholders to get involved in CLSC. In order to maximise profit, how to design a CLSC network is crucial. In general, a CLSC network consists of manufacturer, remanufacturer (including collector, inspector, dismantler, recycler), and disposal site (Amin and Zhang, 2012). Alumur et al. (2012), through applying a multi objective mixed-integer linear programming (MILP) model, propose a profit maximisation modelling framework for RL network designing. This framework is flexible to most of the reverse network structures and is able to accommodate future adjustments.

It is noted that MILP appears to be the most popular tool in network designing. Amin & Zhang (2011) applied a MILP model to maximise profit by determining quantity planning in the network; Fernandes et al. (2010) and Chaabane (2011) introduced a multi-period MILP based framework for CLSC and sustainable SC network design respectively; Dai and Zheng (2015) extended a multi-objective MILP to a multi-product, multi-echelon CLSC network design. Krikke (2011) focuses on reducing environmental impact when designing a network. While the review suggests that MILP is a useful tool in designing a network, however, more comprehensive methods are needed that can better reflect the stochastic features in RL and non-linearity in CLSC.

There are number of derivative MILP models in CLSC network design. A stochastic programming model is proposed by Chouinard et al. (2008) and Lee et al. (2010). It aims at evaluating the impacts of randomness related to recovery, processing and demand volumes on the design decisions. Ko and Evans (2007) and Du et al. (2009) construct a Mixed Integer non-Linear Programming (MINLP) model to facilitate a CLSC network design, while Kaya and Urek (2016) analyse a network design problem in a facility location-inventory-pricing model. El-Sayed et al. (2010) developed a multi-period multi-echelon network, by a stochastic mixed integer linear programming (SMILP) method.

There are other operational performance measures in RL and CLSC:

- Capacity utilisation (Cruz-Rivera and Ertel, 2009; Francas and Minner, 2009);
- Coverage of customers (Lee & Chan, 2009);
- Efficiency of planning process (Das & Chowdhury, 2012);
- Enhance service through planning transportation (Du and Evans, 2008; Fonseca et al., 2009);
- Increasing product return rate through designing recycling network (Aras and Aksen, 2008; Cagno et al., 2008; Kusumastuti et al., 2008; Kara and Onut, 2010);
- Minimising environmental impact (Diabat and Simchi-levi, 2010; Kannan et al., 2012);
- Minimising total cost (Lee and Dong; 2008; Lee et al., 2009)

- Optimisation of production value and manufacturing and remanufacturing products quantities (Demirel and Gökçen, 2008);

Summarising the above literature, it suggests that the majority of research on RL and CLSC has been focused on profit and cost related measures. There is less research focusing on environmental impact. Nevertheless, it is evident that there is an increasing trend of integrating environmental impact into cost related models. It is noticed that research on measuring social impact in a CLSC is scarce.

While RL/CLSC have been intensively studied in the last two decades, there is still a lack of systematic understanding of system dynamics, i.e. the changing behaviour over a product-life-cycle period. In addition, research on legislative impact has been more focused on qualitative analysis. There is a need for quantifying the legislative impact on product return rate.

2.6 Research on product returns

As mentioned previously, returning is a critical activity of RL management. It is the start point of a RL operation. All activities in RL have either direct or indirect interrelationships with product return. Research in RL field cannot avoid product return issues. The following research areas are the main research issues related to product returns.

2.6.1 Forecasting product returns

To establish a practical RL/CLSC flow, it is important that products entering in the network need to be accurately forecasted. However, due to the uncertain nature of product returning, it is challenging to predict product return rate and evaluate quality of returns. The comprehensive literature review undertaken by Govindan et al. (2014) suggests that literature related to return forecasting is scarce.

This section starts from reviewing the three papers suggested by Govindan et al. (2014), followed by reviewing the specific forecasting methodologies used in forecasting returns.

Firstly, Hanafi et al. (2008) develop a fuzzy coloured Peri Net (FCPN) model which is used to provide a demographics based returned products forecasting. Their research focuses on the WEEE EOL products collection forecasting strategy and analyses how different collection methods (i.e. drop-off collection, periodic kerbside collection, on-call kerbside collection, mail-in collection) affect returns. As the amount of returned products is a critical element within a RL network, the research presents a useful approach to forecast return, hence a better strategy design. Secondly, a set of four dynamic regression models for forecasting returns are proposed by Carrasco-gallego and Ponce-cueto (2009). The research compares the four transfer function models and observes a dominant variable (i.e. probability of initial return) through a case study of a reusable containers' CLSC. Thirdly, Kumar and Yamaoka (2007) reviewed the Japanese automotive industry and SD method to predict the Japanese car market. In order to use SD analysis, a stock flow diagram to visualise a CLSC of the market was developed, in which several factors affecting consumption forecasting were highlighted. Although their research purpose is to forecast car consumption, the approach still provides a good insight into a CLSC by taking into consideration remanufacturers, recyclers, government, manufacturers and customers. The SD simulation result provides a quantitative analysis of the relationships between RL activities, and a regulative incentive in terms of improving used products recycling.

Developing competitive RL operational strategy is another core research. Han et al. (2015) establish a CLSC model focusing on production order decisions considering customer demands and product recovery. The study shows the positive relationship between recovery price and remanufacturing product quantity, and negative relationship between recovery price and optimal planned new products production. Hu et al. (2015) investigate the recovery strategy of

CLSC, and design a retailer-3P recycler recycling mode, which is different from traditional 3P mode. The Stackelberg game model is built to evaluate optimal decisions. Only linear uncertain demand is considered, which is a limitation of the research. Return products collection is also researched by Chuang et al. (2014). In their study, 3 types of collection modes i.e. manufacturer collection, retailer collection, 3P collection, are compared and contrasted. Several factors including economic and non-economic aspects are investigated. They provide insights on how a forward flow should be integrated into a CLSC. In terms of inventory control, Cannella et al. (2016) study the systematic stability related to ordering and inventory. The Bullwhip effect and inventory instability are negatively affected by product return rate, which provides practical insights into companies regarding their attitude towards product return.

2.6.2 Models for forecasting product returns

- SD modelling

Dynamic nature exists in the SC system. To understand it, SD is proposed for SC modelling. Especially, when the bullwhip effect is considered, some modelling methods are not able to explain it. SD emerging from control theory has proved to be a good mathematic tool to analyse SCM.

The application of control theory in SCM is seen in "On the application of servomechanism theory in the study of production control" written by Simon (1952). In the model, servomechanism continuous-time theory is used to control production rate. Later, in the early 1960s Forrester (1961) introduces "industrial dynamics", which is now called "system dynamics". The methodology has been widely used in different research disciplines. Early application of SD in SCM is by Towill et al. (1992). In his model, an inventory and order based production control system (IOBPCS) is presented through a visualised block diagram.

Since then, several models are established considering different inventory and order perspectives. Variable inventory and order based production control system (VIOBPCS) is created by Edghill and Towill (1990) considering variable desired inventory levels and multiple of average market demand. Automatic pipeline, inventory and order based production control system (APIOBPCS) established by John et al. (1994), which introduces WIP and deals with consumption data. Further to this model, Disney and Towill (2005) extend the model into an automatic pipeline, variable inventory and order based production control system (APVIOBPCS) with the inclusion of variable inventory targets. The above models all belong to the IOBPCS family and follow the same rules.

- Product return research techniques

Different forecasting techniques are used for different operations in SCM, e.g. forecasting sales helps resources allocation issues within procurement, manufacturing, inventory, distribution and human resources in the short or long term (Carrasco-gallego and Ponce-cueto, 2009). In a RL system, return forecasting is crucial as the more accurate the return is predicted, the more efficient and practical operations can be planned ahead. However, as mentioned before in this chapter, the complexity of a RL operation largely lies on uncertainties within every stage within it. The quantity and timing forecasting of return are two important issues. Various quantitative methodologies have been applied for solving issues related to return forecasting within RL research. The most common technique used for return quantity forecasting is the classical deterministic exponential smoothing model. This technique heavily relies on historical return data, considering weights assigned to historical observations. Nondeterministic approaches tend to cope with a wider range of uncertainties, which include stochastic approach, fuzzy logic, interval programming, etc.

- Review of grey system theory (GST)

Grey systems theory was firstly developed by Deng (1982). The 'grey' colour represents the degree of clarity of the system under investigation. The theory along with fuzzy mathematics tends to provide an angle of exploring uncertainty within a system. In particular, Deng's GST tends to deal with incomplete information within small samples (Deng, 1982) through acquiring useful information from what is available. Since the theory was proposed, it has inspired and been further developed by many scholars from different disciplines, and a great number of publications related to the theory have been published, e.g. geology, biology, medical science, etc (Liu et al., 2012).

Noise and uncertainty often affect and limit people's understanding when they study systems. As a branch of system science, GST aims to model uncertain systems in which information is incomplete and inadequate (Golinska et al. 2014). Within a SC, uncertainty is one of the most challenging issues (Memon et al. 2015). Stochastic characteristics always appear in decision-making processes and forecasting processes in CLSC management, due to dynamic features of CLSC systems', i.e. information incompleteness and data inaccuracies (Liu et al. 2012).

In terms of GST applications, they can be categorised into the following areas: Grey Relational Analysis, Grey Decision Making and Grey Models. Grey Relational Analysis (GRA) is applied for investigating relations between variables and generalising estimates (Tang, 2015).Grey Decision Making (GDM) researches decision support. As a forecasting model, Grey Model (GM) is a mathematical model that deals with original data and is proposed to forecast time series using small samples. Since the GST was initially introduced by Deng (1982), it has been developing rapidly. Especially within the field of SCM, the theory has been used in research related to decision making, e.g. Morita et al. (1996) on grey forecasting, Kuhnell et al. (1991) on machine condition forecasting, Huang et al. (1995) on grey prediction using GM, Wang (2002) on stock predicting, etc.

Apart from GST, there are three other techniques used to deal with uncertain systems: probability and statistics, fuzzy mathematics and rough set theory (Lin, 2004; Liu et al., 2012). These four methods stand on the same ground as the research objects containing uncertainties. The differences of research objects derive different characteristics of these four theories. Probability and statistics explores the phenomenon with stochastic uncertainty. It requires large samples to acquire certain statistical distribution patterns. Fuzzy mathematics deals with cognitive uncertainty, which has definite internal meaning but unclear external extensions caused by individual subjective recognition. Rough set theory researches indiscernibility between objects through giving the lower and upper approximation. GST focuses on issues that have clear extension but vague intension. It models a small amount of data, which differs from fuzzy mathematics and probability and statistics supported by big samples.

- Review of Graphical Evaluation and Review Technique (GERT)

As a technical method, GERT is a procedure for analysis of stochastic networks. It was developed by Pritsker and Happ (1966). GERT networks are those (1) which have actions which may appear random, but can be predicted as each action will have a probability linked with its incidence; (2) the time required for an action within a stochastic network may be varied, and is therefore not treated as fixed, being a random variable.

Project Evaluation Review Techniques (PERT) networks with certain actions and iterations that have given rise to GERT. GERT networks where uncertainty exists for both the occurrence and time taken for defined actions can be examined by the use of GERT. This will produce graphs to show analysis of feedback loops within a network (Pritsker & Happ, 1966; Whitehouse & Pritzkerb, 1969). GERT representations are derived from multiple linear equations whose functions are to evaluate as well as predict probable actions with a system, to give rise to predictions for the system as a whole (Whitehouse & Pritzkerb, 1969).

(Whitehouse & Pritskerb, 1973). Using GERT sequential, parallel and repeating processes can be examined. The qualitative descriptions of structures are transferred to graphs representing these processes within a network.

GERT networks have been successfully used to model outcomes throughout industry. Simulations have efficiently examined multi-faceted networks predicting, scheduling and analysing varied operations. Huang (1983) presents a Q-GERT network model which simulates various traffic conditions. Shankar and Sahani (1995) study the reliability of a system containing two independent and identical units using GERT. Kurihara and Nishiuchi (2002) propose a GERT network to estimate changes caused by activities changes and sensitivity. Shankar and Mohapatra (1993) design a repetitive group sampling inspection system through the GERT for the purpose of quality control. Kosugi et al. (2004) evaluate relationships between the R&D processes of different types of CO2 capture technologies and different levels of CO2 capture efficiency.

To summarise, forecasting product return is challenging due to the uncertainties in a RL or CLSC system. Literature in this area is very limited because the conventional forecasting methods cannot cope with the amount of stochastic characteristics. Therefore, as much as forecasting is important, developing new return forecasting must be set in the research agenda.

2.7 Research Gaps

Literature related to RL has been reviewed to identify the following research gaps:

- Study on the impact of legislative and incentive schemes on product returns is important but scarce. In order to enhance profitability in a recycling process, high return rate of used products is encouraged, which can be achieved through either legislative force or economic incentive schemes. Nevertheless, due to the difficulty of quantifying the impact, this area remains unexplored.

- The importance of forecasting in RL/CLSC is as much as in a forward SC. Nevertheless, the conventional forecasting methods used in the forward SC are not able to accommodate the great deal of uncertainties. There is very little research on return forecasting due to extreme challenges. Therefore, developing new forecasting methods of product returns is necessary.

- The RL/CLSC performance has been measured from profit/cost and/or environment aspects. There is a lack of research that can provide a more comprehensive measurement and a better understanding of system dynamic behaviour. Therefore, more integrated models that can reflect the complexity of RL/CLSC and provide profound understanding of system dynamics are needed.

2.8 Summary

The purpose of this chapter is to review current research and explore research gaps. Definitions related to research topics have been stated. Sustainable dimensions are sorted to explain the interrelationships between causal factors and product return. In addition to this, a CLSC is divided into several stages. Each stage and the main activities involved in each stage are identified. Current research is further categorised into qualitative and quantitative research. Literature related to RL operations is reviewed. Research relating to product return has been reviewed from a forecasting perspective. Different modelling techniques are also discussed. Hence, three research gaps have been identified.

METHODOLOGY

Chapter 3. Research Methodology

3.1 Introduction

The research theme and research objectives have been established in the previous chapters. The purpose of the research methodology chapter is to detail the place of this thesis in comparison with other significant research paradigms. It explains the research methods and strategy used to meet the objectives for this research given in Chapter 1. This chapter is structured to answer the question of how this research is undertaken. This is achieved by detailing what is the scientific research paradigm of the proposed research; what research strategy is used to plan this research; what research methods are employed to facilitate the research objectives.

Research methodology is vital and fundamental. This is because it forms the foundations for the research questions which can be answered, and the type of data that is produced (Clark et al., 1984). The type of methodology chosen can impact on how research outcomes are used. For example, among interpretive research the goal of it is to explain a specific case, which is not the same as the positivist approach which tends to generate universal research outcomes (Schofield, 1993). Therefore, the aims of the research have been used to select the research methodology chosen.

3.2 Research Paradigm

The basis of successful research lies with the methods selected for study. The choice of these methods should be motivated by and suitable to the research questions to be answered (Abernethy & Brownell, 1999). Additionally, the methodology should reflect the research paradigm within which it lies, and real world which is understood by the researcher. When a research objective is designed, "A methodology is a collection of procedures, techniques, tools and documentation aids... but a methodology is more than merely a collection of these things. It is usually based on some philosophical paradigm; otherwise it is merely a method, like a recipe" (Avison and Fitzgerald, 1995, pp.63). Four main research paradigms were identified by Guba and Lincoln (1998). These are positivism, post-positivism, critical theory and constructivism. Table 2 and table 3 illustrate the above paradigms using three defining paradigm elements: ontology, epistemology and methodology (Blanche et al., 2007).

Table 2. Paradigm-Defining Elements (Guba and Lincoln, 1994; Saunders et al., 2009; cited by Mohamed, 2012)

Positivism<--> Phenomenology

Orientation	Positivism	Post positivism (realism)	Critical theory	Interpretivism/ Constructivism
Ontology	'Naive realism' in which an understandable reality is assumed to exist, driven by immutable natural laws. True nature of reality can only be obtained by testing theories about actual objects, processes or structures in real world.	Critical realism - 'real' reality but only imperfectly and probabilistically apprehendable.	Historical realism - social reality is historically constituted; human being, organizations, and societies are not confined to existing in a particular state.	Relativism - local and specific constructed realities; the social world is produced and reinforced by human through their action and interaction.
Epistemology	Dualist/ objectivist; verification of hypothesis through rigorous empirical testing; search for universal laws of principles; tight coupling among explanations, predictions and control.	Modified dualist; objectivist; critical tradition/ community; findings probably true.	Transactional/ subjectivist; knowledge is grounded in social and historical practices; knowledge is generated/ justified by a critical evaluation of social systems in the context of researchers' theoretical framework adopted to conduct research.	Transactional/ subjectivist; understanding of the social world from the participants' perspective; through interpretation of their meanings and actions; researchers' prior assumptions, beliefs, values, and interests always intervene to shape their investigations.
Methodology	Hypothetical - deductive experiments/ manipulative; verification of hypotheses; chiefly quantitative methods	Modified experimental/ manipulative; falsification of hypotheses; may include quantitative methods	Dialogic/ dialectical; critical ethnography; interpretive case study; action research	Hermeneutical/ dialectical; interpretive case study; action research; holistic ethnography

Table 3. Points of contrast: positivist and interpretivist approaches (Sumner and Tribe, 2008)

	A Positivist Approach	An Interpretivist Approach
What is 'reality'?	A definable 'reality' or 'truth' that exists and is observable.	There is no 'reality' or 'truth' beyond experiences.
What is the goal of academic enquiry?	Acquisition of the 'truth'	A more informed construction of the world
How are the researcher and the 'researched' related?	The researcher is independent of the 'researched'.	The researcher is not independent of the 'researched'.
What should be the roles of values?	None-objectively sought.	Part of 'reality' - subjectively celebrated.
What kind of approach?	Predominantly based on observability or measurability and with the aim of seeking 'evidence'.	Predominantly based on discourse and meaning with the aim of seeking a more informed understanding of the world.
What kind of data is preferred?	Predominately quantitative	Traditionally associated with a predominantly qualitative approach.

3.3 Supply chain management research paradigms

Discussion related to paradigms of SCM are limited (Wolf, 2008). Due to the Differing academic backgrounds of researchers working in the area of SCM they tend to solve their research issues from different epistemological perspectives (Asbjørnslett, 2008). Most researches have fallen into either positivism or interpretivism. Others apply intermediate approaches. The nature of the phenomena existing in the proposed research objectives involves different causal interrelationships between different elements and processes. According to Gammelgaard (2004), there are three categories existing in SCM research: analytical, systems and actor's approaches (Table 4).

Table 4. Methodological framework of SCM research

	Analytical approach	Systems approach	Actor's approach
Theory type	Determining cause-effect relations. Explanations, predictions. Universal, time and value free laws	Models. Recommendations, normative aspects. Knowledge about concrete systems	Interpretations, understanding. Contextual knowledge
Preferred method	Quantitative	Simulation and case studies	Qualitative
Unit of analysis	Concepts and their relations	Concepts and their relations	People - and their interaction
Data analysis	Description, hypothesis testing	Mapping, modelling	Interpretation
Position of the researcher	Outside	Preferably outside	Inside

Source: Gammelgaard (2004) cited by Spiegler (2013)

As the result of being both theory-driven and reality-influenced, the system approach is considered to be an intermediate approach. As another important method in the research, the mathematical analysis is used as an analytical approach to interpret causal relationship between elements identified by the research.

3.4 Paradigms of the research

In general, four types of research paradigms can be applied for research work, depending on if the research is more positivist in its orientation or more phenomenological in its orientation. Three criteria are used to define which type of paradigm a research falls in, i.e. ontology, epistemology and methodology. However, often research falls into an intermediate research paradigm. This research is one such example. The paradigm position of the research is that researcher agrees that all types of research involve some extent of subjectivity, i.e. researcher's belief. However, the researcher also accepts the existence of a real world. 'Constructivist realism' is a research paradigm that the researcher agrees the realism exists in a real world and constructivism is the way how to define the reality.

3.4.1 Ontological position of the research

Metaphysics is a term used to describe the philosophy of reality understanding and theories developing, through the knowledge we have and is existent Gammelgaard (2004) cited by Spiegler (2013). A stem of metaphysics is ontology which addresses the nature of a reality. Within this, a key question is if social structures are influenced and built from the actions and perceptions of those within them (Sumner & Tribe, 2008). To ensure objectivity within the research the research object is understood to be independent and not linked to opinions and interpretations of the researcher.

3.4.2 Epistemological position of the research

Stemming from ontology there is epistemology. This is a philosophy that investigates 'what it is we know' and 'how we know these things', looking at the breadth of knowledge and where knowledge has originated from (Guba and Lincoln, 1994; Saunders et al., 2009). The epistemological position separates the reality on the ground (positivist) and human understanding (interpretivist). Key to this is realism which is built on the ontological understanding that the reality on the ground exists separately from human understanding. Positivism shows a researcher as being independent from the object which is being researched and has no bearing on the object being researched. Models and structures put forward by the research are built upon the researcher's cognition of the reality. Objectivity is applied when designing criteria which are used to explain the research concept of ideas and models established within the research. The aim of the research is to understand product returns in a CLSC, i.e. what factors influence it, and how they affect it; what its impacts are and how it works in the system. Therefore, the research investigates the existing SCM reality and also tries to question the common social constructions.

3.4.3 Methodological position of the research

This research relies upon various quantitative methods. A qualitative approach also has been used within the thesis, in the literature review. Complementing each other, qualitative and quantitative methods provide differing visions of the issues being researched. By using both approaches, accurate outcomes can be achieved; this implies that richness can enhance precision because the in-depth account encompasses more information, while a focus on precision can lead to a clarification of basic concepts (Cupchik, 2001). The multi-method approach is used within SCM research, giving rise to robust results.

The quantitative method adopted in this research is mathematical models in the forms of (Albright & Winston, 2011, pp.20-29): differential equations, e.g.

Chapter 4; statistical graphical evaluation and review techniques, e.g. Chapter 5; and dynamical systems, e.g. Chapter 6. The reasons for the use of mathematical modelling - the process of developing mathematical models - as the quantitative methodology are:

- Mathematical models can closely reflect reality;
- Analysis of the models can answer what-if type of research questions;
- The result of analysis often can provide managerial insights; therefore
- The result of modelling could offer recommendations for an action plan.

3.5 Research Strategy

Here the selection choices influenced by the ontological approach explained in section 3.4.3 are detailed. Easterby-Smith and Thorpe (1991) identified three different approaches to deliver a research aim, inductive reasoning, deductive reasoning and abductive reasoning.

The first stage of inductive reasoning uses ideas from observation. From these observations, generalised theories can be generated. Inductive reasoning initial ideas generated from observations are referred to as 'the initial base'. From these observations, generalised conclusions known as 'hypothetical rules' will generate research content, but this content is not wholly reliable because a hypothetical rule is just that, hypothetical, and cannot be proved beyond doubt. On the other hand, deductive reasoning is based upon a theoretical concept and studies are undertaken to confirm the given theoretical concept or prove a hypothesis. By its very nature inductive reasoning can give rise to a greater breadth of results than deductive reasoning. Both inductive and deductive reasoning usually occur in combination at the same time (Glaser, 1992). The thesis uses a combination called abductive reasoning. Initially similar to inductive reasoning, i.e. generating research questions based upon observations, abductive reasoning constructs a circular flow connecting theory generated processes and actually observed practices. Literature can be based upon vague generalised concepts or conversely too rigidly guided by an established theoretical model. Through the use of abductive reasoning the research has a flexible research strategy, allowing new hypotheses and ideas to be incorporated and in turn new theoretical ideas generated. Abductive reasoning within logistics has been shown to support the creation of new theories (Kovacs and Spens, 2005).

The reason for selecting abductive reasoning is that analysis of product return in a CLSC has been found to have limited availability. The systems thinking nature of the study is presented, as the investigation on product returns involves cause and effect from various factors and different mechanisms in a CLSC. As the systems thinking approach has not been clearly defined as either deductive or inductive, or either positivism or interpretivism, it is considered as an intermediate approach. Because of the nature of the research questions, abductive reasoning allows the researcher to explore the interrelationships between the criteria and product returns, hence developing new concepts related to product returns effects.

3.6 Research methods

This section presents the methods and tools applied for the research, i.e. exploratory, explanatory, or descriptive approach. The choice of research methods follows the decisions involved in selecting the research strategy based on the ontological and epistemological position of the current research as outlined in the previous sections. It is also driven by the social phenomenon to be studied and by the research questions. A research can be empirical, where data from field research is applied. A research strategy can also be conceptual, where no field data is used to establish the research results (Wolf, 2008). According to this, the thesis is conceptual research. It follows a conceptual research strategy, which doesn’t rely on data gathered from an empirical field study. As conceptual research, this research includes an exploratory part, which aims to ask questions to find out what is happening and a structured part, which further tests models built (Denyer and Tranfield, 2006). The former refers to a conceptual review through literature, the latter is predominant in the research, which includes mathematical modelling and simulations.

3.6.1 Exploratory conceptual research

A literature review is conducted during all phases of the study and includes analysis of books, academic journals, conferences and workshops proceedings. To achieve the aim of literature review, content analysis has been employed within a wide range of literature to explore the "ideas". Krippendorff (2012, pp.24) argues that contemporary content analysis serves as a research method to make "replicable and valid inferences from texts (or other meaningful matter) to the contexts of their use". The aim of the content analysis is to identify the criteria considered to affect and being affected by product returns within a CLSC, and propose a model for future study. For this, it requires the extraction and derivation of considerations addressed within a large amount of existent literature related to the research theme, the relevant content may reveal a solution to the research question. Therefore, content analysis is adopted to review relevant literature and form a theoretical construct for further analysis.

Sampling within a content analysis is to limit available resources in order to create a manageable body of texts, because it is impossible to examine "all texts of a particular population of texts" (Krippendorff, 2012, pp.114). Limited resource may cause bias, so the purpose of the sampling plan is to minimise such bias. Snowball sampling is one of the sampling techniques used. It starts with an initial sample of units, e.g. a recent piece of literature, then the cited works for its references are examined, and finally it ends when it reaches its boundaries, such as no new references. However, Krippendorff (2012) has also pointed out that snowball sampling can generate an exponential sample size. So it is accepted that some constraints should be applied to limit the sample size to ensure that this is manageable.

In this research, "RL disposition decision-making" (Hazen et. al, 2011) is used as the initial core literature, due to the subject being relevant to the topic of the thesis, and its references are used as a literature resource to generate criteria. Because the journal paper was published in 2011, and the latest reference cited within the paper was written in 2010, there is a 6-year gap between the paper being written and now. To avoid bias and update the sample, other journal papers have been updated since. In order to limit sample size avoiding sample explosion or exhaustive results (Webster and Watson, 2002), only the top journals from operations management and supply chain management are selected.

3.6.2 Structured conceptual analysis

The structured conceptual research in this thesis includes mathematical modelling and simulation. To explain interrelationship between different criteria and product returns, mathematical language is firstly used to quantitatively mimic reality, which is presented in Chapter 4. Mathematical language is also applied further in creating a product return forecasting model in Chapter 5 and a CLSC model consisting of a forward SC and a remanufacturing loop in Chapter 6. As a crucial part of the research, the structured conceptual analysis involved in this research is an additional detail presented in the following section of this chapter.

3.7 Structured conceptual analysis and research tools

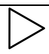
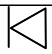
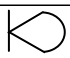
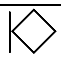
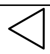
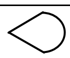
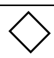
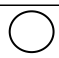
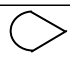
3.7.1 Mathematical modelling

In this research, mathematical modelling has been adopted to quantitatively explain phenomena examined. Different equations and differential principals are obtained in the research. In terms of analysing legislative impacts on products return, a simple mathematical equation is used to interpret interrelationships among legislative enforcement, green awareness, product returns over a continuous time period, e.g. PLC. Within this interpretation, qualitative factors, e.g. legislative enforcement and green awareness, are quantified. Customer return behaviour over a period of time is then established as an equation.

3.7.2 Graphical evaluation and review technique (GERT)

GERT has been adopted to develop a product return forecasting model in Chapter 5. GERT was initially developed as a procedure for (1) analysing networks that contained activities that had a probability of occurrence associated with them, and (2) treating the plausibility that the time to perform an activity was not a constant, but a random variable (Pritsker and Happ，1966). The technique has been widely accepted and implemented in the area of project management (Ahmed, et al., 2007), dynamic scheduling (Pena-Mora and Li, 2001), and uncertainty management (Lin et al., 2011), etc.

The inputs of the GERT are parameters for each activity. Activities are represented by nodes. The input parameters consist of the probability, estimated time period for each activity and the product original structure. In the GERT network, each node is presented by a different icon. In the inputs, there are three types of relationship: XOR, OR and AND. Outputs have two types of relationships: non-deterministic and deterministic. In total, there are six logic nodes:

Input/output	Deterministic 	Non-deterministic 
XOR 		
OR 		
AND 		

In the GERT network, a line with an arrow means a job and each line has two parameters: probability, which means the possibility of doing the job; and time, which means the duration of the job.

In this research, we integrate Mason's (Mason, 1956) rules in the GERT network in order to obtain the transfer function between two nodes. The equivalence transfer function is written as:

$$W_{E_{ij}}(s) = \frac{\sum_{l=1}^{n} G_l \Delta_l}{\Delta}$$

Where G_l is the gain of the l^{th} forward route from i to j, and Δ_l is the loop gain of the l^{th} loop, lϵ{1, n}, and must be an integer. Δ is the determinant of the graph, where

$$\Delta = 1 - \sum L_x + \sum L_x L_y - \sum L_x L_y L_z + \cdots + (-1)^k \sum \cdots + \cdots$$

Where L refers to a loop, $\sum L_x$ is the sum of the transfer coefficient for different loops, $\sum L_x L_y$ is the sum of the transfer coefficient for two non-touch loops, $\sum L_x L_y L_z$ is the sum of the transfer coefficient for three non-touch loops, $(-1)^k \sum \cdots$ is the sum of the transfer coefficient for k non-touch loops ....

The Moment-Generating Function (MGF) is used to describe a random variable's probability distribution as an alternative specification. MGF offers a different method of analysing results through the weighted sum of random variables from the cumulative distribution function (CDF) or probability density function (PDF). The MGF of a random variable *t* is defined:

$M_t(s) = E(e^{ts}),\ \ s \in R$, where this expectation exists.

The Mason-GERT method adopted can be described in eight steps:

Step 1: Mapping the process in order to derive the causal flow chart;

Step 2: Translating the flow chart into the stochastic network;

Step 3: Estimating each activity's parameters (from node i to node j): probability P_{ij} and time probability density function $f(t_i)$:

Step 4: Integrating the two parameters of each activity (i, j) into one transfer function $w_{ij}(s)$: $w_{ij}(s) = P_{ij}M_{ij}(s)$. Where $M_{ij}(s) = E(e^{t_i s}) = \int_{-\infty}^{+\infty} e^{t_i s} f(t_i)dt_i$ is a MGF.

Step 5: Applying Mason's rules to calculate total equivalence transfer function $W_{E_{0j}}$ from initial node 0 to node j based on the network structure and the value of $w_{ij}(s)$. This is a rather complex calculation but indeed a key stage.

Step 6: According to the definition of MGF, the probability $P_{E_{0j}}$ of the activity from initial node 0 to j is $P_{E_{0j}} = W_{E_{0j}}(s)\Big|_{s=0}$;

Step 7: According to the characteristics of MGF (Pishro-Nik, 2014, pp.324-329), the expected return time from initial node 0 to node j is:

$$E(t) = \mu_1 = \frac{\partial}{\partial s}[M_{E_{0n}}(s)]|_{s=0} = \frac{1}{P_{E_{0n}}}\frac{\partial}{\partial s}[W_{E_{0n}}(s)]|_{s=0};$$

Step 8: The predicted quantity is calculated.

The application of GERT networks is provided in Chapter 5.

The justification for adopting Mason-GERT in forecasting of product returns lies on the stochastic features of a product return network and product structure itself: activities in remanufacturing operational process having a probability of occurrence associated with them; and time to perform an activity. These match the characteristics and requirement of GERT (Pritsker and Happ，1966). In addition, the GERT method also can handle a process having a feedback loop – reuse and recycling in our case – where very few forecasting methods could deal with this.

The Mason's rules (Mason, 1956) that we embedded in the GERT method have been commonly applied in control theory. By using Mason's rules, the dynamic relationship of input and output can be quantified. In particular, the output/input transfer functions can be precisely derived. These transfer functions enable complex analyses of the model which leads to analytic results. This is similar in the product return process where each stage has input(s) and output(s). The output can be predicted based on the relationship to the input.

3.7.3 System dynamics modelling

SD modelling is adopted to analyse the dynamic performance of the CLSC with the focus on how product return impacts on inventory level and product ordering. SD was introduced by Forrester (1961) in the early 1960's. It was initially for understanding industrial management issues related to long-term decisions. Sterman (2000) reviewed SD method. He mentioned that Towill et al. (1992) studied production distribution systems using SD method, and Wikner et al. (1991) explained strategies related demand by SD. These two studies can be seen as the early studies of SD.

To understand product return in a manufacturer-centred system, we start from mapping the process in a CLSC, and identifying the relationship between each process, i.e. causal loop, and quantifies the effects of each input on the output(s). This methodology has been widely used in many cases, such as population (Homer and Hirsch, 2006), ecological (Toro and Aracil, 1988) and economic (Sherwood, 2002) systems. SD modelling is implemented to gain a better understanding of the simulated causal effect of product return on the CLSC system. As it has been mentioned in the previous literature review chapter, SD approach has been widely accepted as a research methodology by SC researchers.

To apply SD approach, a diagram is drawn to identify the causal relationship in the system examined. The cause and effect relationships between variables are presented by causal loops. As Forrester (1961) mentioned, a SD model consists of four elements, i.e. levels, flow rates, decision functions and information channels. Within a product return system, variables values (i.e. quantities) are presented by variable levels. The relationships between each pair of measured variables are interpreted by mathematic equations functioned by rates. Rates within the system can be divided into inflow and outflow rate, which depends on whether or not the flow comes into the system. Decision functions are a mathematical explanation of how levels change in the system. It is controlled by the rates and determined by the policies. Information relating to the levels are connected by information channels.

Continuous time modelling and discrete time modelling are two types of SD modelling domain (Zhou, et al., 2010). The main difference is whether the level status is reviewed continuously or not over a monitored time period. This leads to the application of the different mathematical approaches: the former using differential equations while the later difference questions. However, the qualitative meaning gained from the two approaches are basically similar. In this study, continuous time domain is studied by using Laplace transfer functions and control theory.

The reasons for adopting SD methodology in this research are: (1) SD as a research methodology provides an insight into a complex system, by considering processes, elements, interrelationships, boundaries, inputs/outputs, control, etc. It allows various research methodologies to work together to solve systematic issues, and maximise the strength of different methodologies (Jackson, 2001). (2) A SD model requires model behaviours having certain "dynamic patterns" (e.g. exponential growth/collapse) rather than accurate input data required by some discrete-event simulation methods (Vlachos et al., 2007), it gives more flexibility in simulating a long-term process. (3) SD method can reflect both linear and non-linear cause-effect interrelationships. (4) As the ultimate purpose of the research is to provide RL participants with advice on under what circumstances, what their dynamic performance pattern would be.

The SD method is used to produce such outcomes. Taking into account the reasons addressed above, the system dynamic approach is adopted.

According to Kumar and Yamaoka (2007), two stages in the process of SD methodology are a) developing causal loop diagrams and b) dynamic modelling. Microsoft Excel is then used to simulate the SD model. It allows the researcher to visualise the results and check the errors within the modelling process. The development of a SD model of a CLSC and its analysis of dynamic performance are presented in Chapter 6.

3.8 Summary

This chapter positions the current research within the constructivist realism paradigm and provides an overview of the choices, which are made with regards to research strategy and research methods. The scientific position has implications for the choices of research scope and data. The next three chapters present the application and findings from the mathematical models by adopting above mentioned research methodologies.

DISCUSSION

Chapter 4. The impact of legislative and environmental motivations on customer return behaviour

4.1 Introduction

Objective 2, as mentioned in Chapter 1, is to assess legislative impact on customer return behaviour in a CLSC. In this chapter, objective 2 is achieved through mathematical modelling with a focus on policy makers and customers (Figure 6).

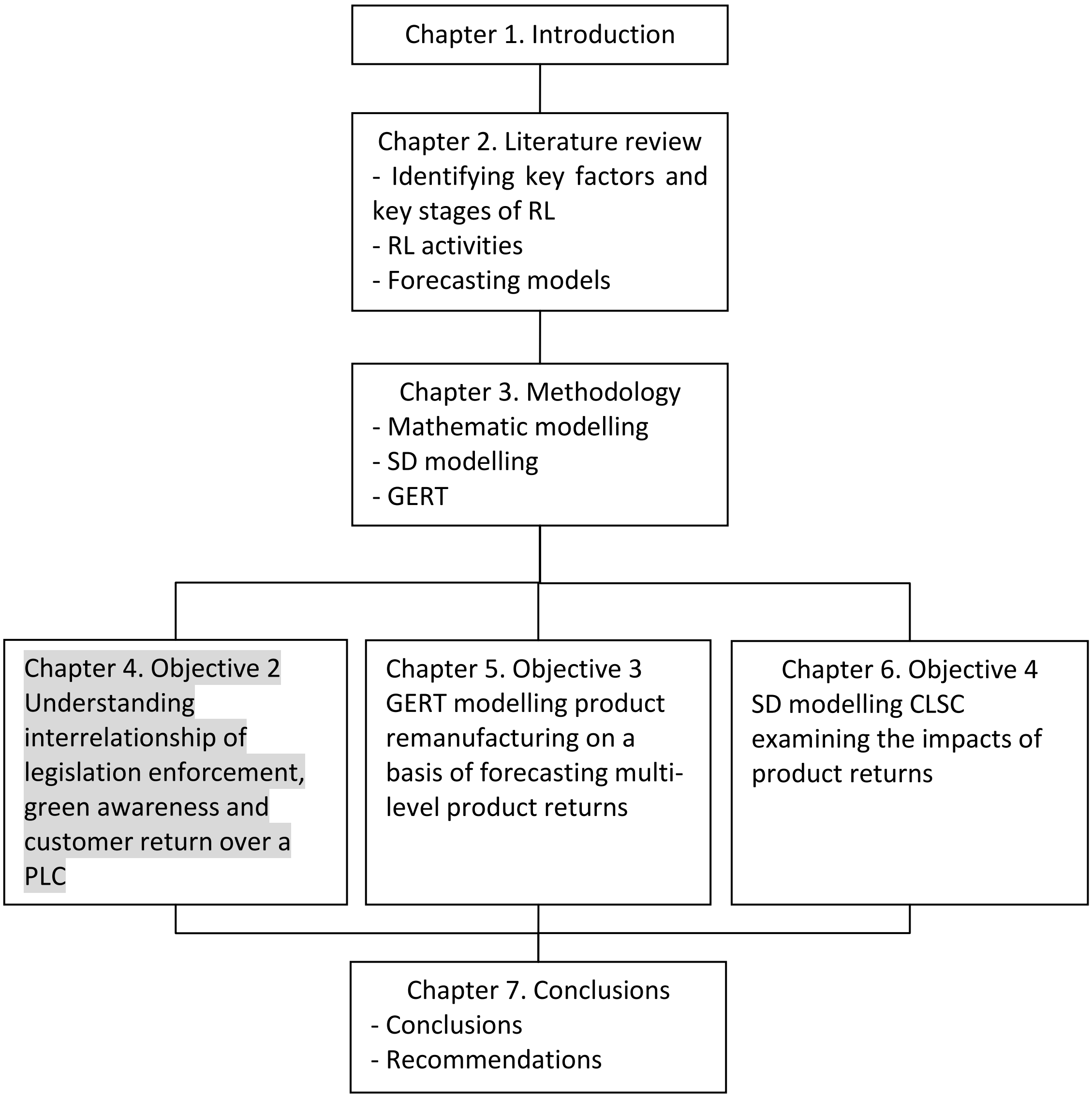


Figure 6. Flow chart of the thesis structure focused on Objective 2 (Source: author)

In this chapter, the research focuses on the background issues of the Chinese electronics manufacturing industry. The chapter starts from (1) identifying and setting up the model for analysis, (2) modelling two propositions based on different levels of customer awareness. The analysis of this chapter aims to analyse customer behaviour under different legislative circumstances, and the final result is further analysed to gain a better understanding of product return and demand.

4.2 Model and propositions description

The key participants in a RL system include retailers, manufacturers, recyclers, customers and government. To promote a circular economy, government often provides subsidy to the entities involved in RL operations. For instance, in China, the government subsidises customers who return their EOL products back through an authorised channel, i.e. authorised recyclers. The government also supports manufacturers who produce energy-efficient products through providing tax deduction/subsidy. In this chapter, we look into how the government incentives, i.e. subsidy, works and to what extent it stimulates customers to return products and the involvement of manufacturers in RL operations. In order to focus on the main issues and assess government incentive impact on customer behaviour, the RL operational procedures applied for this research have been simplified.

4.2.1 Government sponsored RL operation

In this Chapter, as shown in Figure 7, we focus on government sponsored RL where three main participants are involved: manufacturer-retailer-recycler (MRR) bond, customers and government. This is a simple CLSC, that is: the manufacturer produces products, they are delivered to a retailer who sells to customers; customers return the EOL or malfunctioning products to a recycler, as shown in Figure 7. The product flow (solid lines) within the procedure used to set up the model for this thesis starts from ① customers return their used products back to the system through recyclers; ③recyclers pass the returned products to dissemblers for reprocessing; ⑤reprocessed products are sent to OEM for production; ④new products produced by OEM are sent to retailers; ② customers purchase products from retailers; ⑥ customers can choose to dispose of used products as well. The cash flow (dotted lines) within the procedure includes: ①②government subsidises customers to return products through authorised recyclers; ③④OEM either receive subsidy or penalty from government depending upon their production.

A detailed elaboration is as follows:

- The manufacturer can produce either energy-efficient or non-energy efficient electronic products. The decision depends on two factors: (1) profitability which is affected by customer demand. We assume that customers can choose to purchase either energy-efficient or non-energy-efficient products. Their purchasing decisions are based on customers green awareness, government's encouragement/enforcement and product price; and (2) a manufacturer’s environmental conscience. In our model, only factor (1) is considered.

- Customers decide whether or not to return their EOL electronic products back to recyclers. The decision can be affected by economic benefits which they could get from returning products, for instance a trade-in programme; government enforcement, for instance hazardous products/materials handling regulation requires proper disposal of them; and customer green awareness, for instance customers with higher environmental and ecological cognition can lead to their return behaviour/purchase behaviour being more motivated by environmentally and ecologically friendly actions.

- Recyclers, if they are authorised by government, can undertake a series of correct RL processes. Depending on the returned products quality, the reprocessing process could include sorting, cleaning, reselling, refurbishing, dismantling, remanufacturing, recycling and disposal. After reprocessing, the used products are fed back into the CLSC in the form of either refurbished products or parts or materials.

- Government plays a crucial role in RL. It governs the system through legislative enforcement, incentive schemes and penalty mechanisms. In order to motivate customers to return products and manufacturers to produce energy-efficient products, for example, in China, the government subsidises manufacturers who take back used products to undertake remanufacturing, so manufacturers who benefit from this would partially pass this economic benefit to end users in order to encourage the return of used products, through trade-in of used products or sharing costs with authorised recyclers to achieve a higher product return rate or a lower reprocessing cost. In addition, there is a tax exemption scheme for manufacturers who invest in green products, i.e. manufacturers who produce energy efficient products benefit through a VAT exemption or deduction; or a penalty is in place if a manufacturing process generates considerable environmental and/or ecological harm.

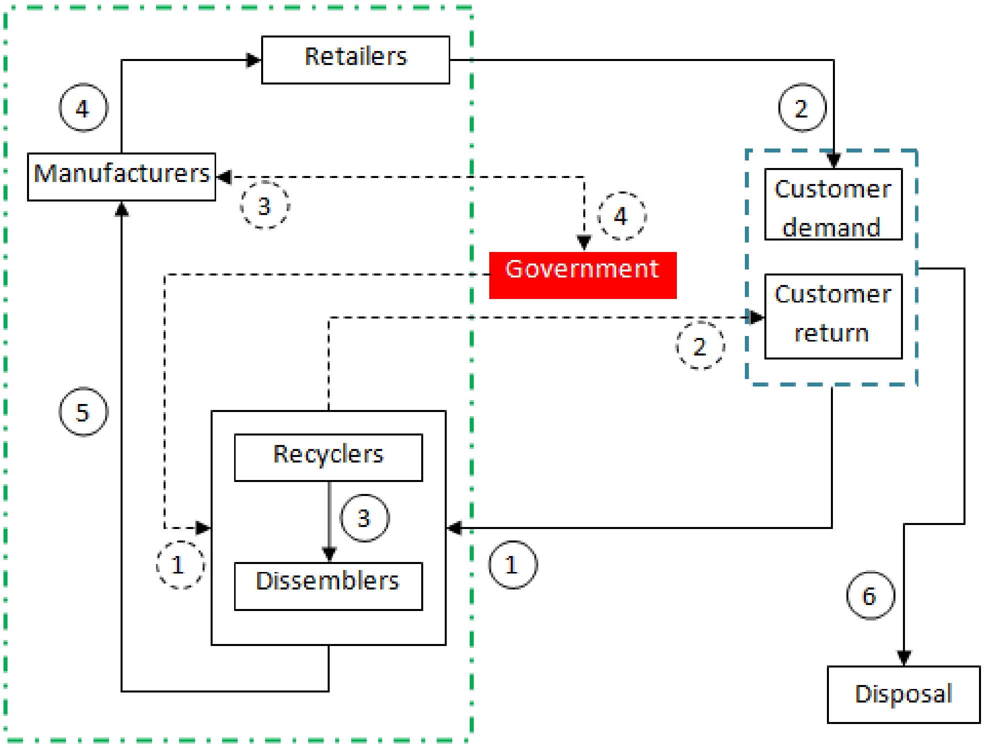


Figure 7. Flow chart of a government involved RL procedure

4.2.2 Research propositions

To assess how different incentive policies affect a RL operation, the following two provisional legislative policies are set up to examine customers' responses under differing legislative scenarios.

Proposition 1. Government subsidises only during the first observed time period; the subsidy is provided when the products owned by customers are returned back to authorised recyclers regardless what the type of product is, energy-efficient or not.

Proposition 2. Government subsidises during the first and second observed time periods. During the first time period, subsidy is provided when previous products owned by customers are returned back to authorised recyclers; during the second time period, subsidy is only provided when EOL energy-efficient products are returned back, non energy-efficient products do not receive any subsidies.

Proposition 1 is modelled to simulate current recycling subsidy strategy where the Chinese government is trying to pay a competitive price for customers who recycle used products through an authorised channel, while proposition 2 is modelled to examine whether and how subsidy differentiation would affect customer purchasing and recycling behaviour, i.e. whether legislation can lead to green purchase and return behaviours and how it works.

4.2.3 The implication of the S-shape growth in product life cycle

Many systems' growth follows the law of natural growth as "an initial slow change, followed by a rapid change and then ending in a slow change again" (Kucharavy and De Guio, 2008, p81). As a visualised figure, a bell-shaped curve is used to illustrate such a process within a time span. It is well known as PLC, in Figure 8.

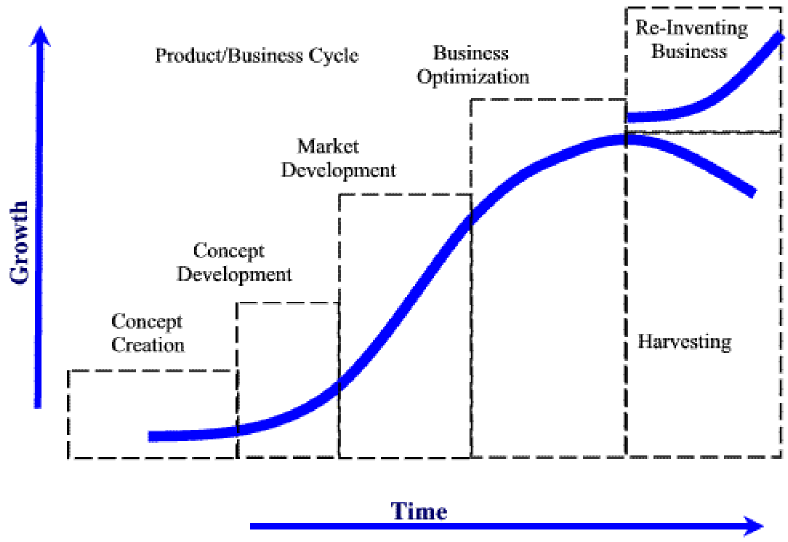


Figure 8. S-shape curve of five stages within a PLC

As a well established theory, the PLC theory has been around for over 60 years (Dean, 1950). The PLC theory is commonly recognised as a pattern which interprets a new product's sales over its life time span on the market. It includes 4 or 5 stages: introduction, growth, maturity (or/and) saturation and decline (Tibben-Lembke & Rogers, 2002). The sales over time of a life span increase until they reach a peak at a stage of saturation, and then new products replace the 'old' products. The total amount of sales during a life-cycle keeps increasing. The sales growth rate varies from different stages: i.e. from a positive number at the first three stages to a negative number at the stages of saturation and decline. To find the cumulated sales at any given point within this time span, it follows an S-shaped curve.

An S-shaped curve has been applied for forecasting since the early 19th century (Kucharavy & De Guio, 2008). Simply because it interprets the law of nature, identifies the boundary of growth and speed of growth.

An S-shaped growth/curve has been implemented within the models for the following two reasons:

(1) It represents the inertia of customer return behaviour to environmental legislation at different strengths;

(2) It represents the inertia of customer demand towards time span to reflect the PLC pattern.

They can be interpreted as,

- the amount of customer return, Q_R, is modelled as a function of legislative enforcement and time with a general form of:

$$Q_R(t) = Q_0\left(a + Tanh\left(2T * ELI^T\right)(1-a)\right)Tanh\left(t\left(\frac{t}{1+t}\right)^T\right) \tag{4.1}$$

Where a is a scale parameter which can be seen as the index of customers green awareness, Q_0 is the initial quantity of products previously sold and owned by customers, *T* is the time period within which environmental legislation is implemented, *t* is the time from which customer return is affected by legislation and time. The first Tanh function: $Tanh\left(2T * ELI^T\right)$ represents the inertia of customer return to legislative strengths; the second Tanh function: $Tanh\left(t\left(\frac{t}{1+t}\right)^T\right)$ represents a time buffer. Together, the total customer return is formulated considering: customer's green awareness, legislative strength and time. It follows a S-shape curved trend.

- The accumulation of customer return at time $t, t \in \left(0, T_1\right)$ in period 1 can be formulated as following:

$$Q_r(t) = Q_0(a_1 + Tanh(2T_1 * ELI_1^{T_1})(1-a_1))Tanh[t(\frac{t}{1+t})^{T_1}] \tag{4.2}$$

Where a_1 is the customer's green awareness during the first time period, ELI_1 is the environmental legislative index (i.e. legislative enforcement) during the first time period.

- The second S-shaped growth is a mathematic interpretation of customer demand behaviour within a time span is as Equation (4.3). As over the time span, customer demand for a product experiences five stages birth, growth, maturity, decline and death. The life span is called a PLC. Customer demand $Q_D\left(t\right)$ can be modelled as:

$$Q_D\left(t\right) = Q \times Tanh\left(t\left(\frac{t}{1+t}\right)^{PLC}\right) \tag{4.3}$$

Where *Q* is the estimation of customer demand. This formula represents accumulative sales at any t, i.e. accumulative customer demand for a product from when it is introduced into a market to the time t.

4.2.4 Model assumptions

Customer return and customer demand are compared to closely examine the impact of legislation. To calculate the above outputs, the input data is considered based on the following estimations.

4.2.4.1 Assumption of products-in-use

Unlike much previous research, the quantity of products-in-use used in the research does not come from the historic data. Instead, we assume it is a unit, i.e. 1. There are two types of products-in-use within a model; Q_0 is the initial products aimed to be returned during the first time span. The quantity of the second type of products-in-use Q is derived from the sales in the first time span. It includes both energy-efficient and non-energy-efficient products regardless if an incentive is in place.

4.2.4.2 Assumption of sales

As mentioned above, the sales include sales of two types of products, i.e. energy-efficient and non-energy-efficient products. Due to the two types of products in the model serving a similar function, the difference between their sales is affected by their prices. In general, the higher the price is, the lower the sales are. However, subsidy to customer return can be seen as a purchase cost reduction. Sales are also affected by time, as customers demand for a new product experiences a S-shape growth.

4.2.4.3 Assumption of legislation and customer green awareness

Legislation and customer awareness together affect customer returns. The greater the legislative enforcement can cause a potentially greater customer return. Similarly, the more the customers realise the importance of environmental protection, the more they tend to recycle their used products. Previous research done by Srivastava (2006) and Vlachos et al. (2007) have recognised legislative impact. However, customer green awareness is not fully explained. In this research, an accumulative effect of both legislation and customer green awareness is evaluated. It decides the customer return percentage. When there is no legislative enforcement, customer return is only determined by customer green awareness, and Vice versa when there is complete legislative enforcement this negates customers green awareness.

4.2.4.4 Assumption of time span

Time span affects the steepness of S-shape growth. Two types of time spans are applied within the research. The first time span represents the period of time which legislation has been in place. The second time span represents the PLC.

Analysis of legislative impacts on customer demand and customer return is undertaken under two propositions. Customer return and customer demand are two outcomes to compare and contrast against the two different legislative propositions mentioned in 4.2.2, and furthermore evaluate the impact of legislation.

4.3 Model description

4.3.1 Modelling customer returning behaviour

Customer returning behaviour is influenced by legislation enforcement, their individual green awareness and time as shown in Equation 4.1 and 4.2. Return rate is modelled by an accumulation of legislative enforcement index (ELI) and green awareness index (a), which interprets the reality as more subsidy (ELI) provided causes a higher returning rate, and higher green awareness (a) leads to a higher return rate. However, the relationship between ELI and return behaviour triggered by the ELI is modelled through a S-shape curve representing the inertia of customer returning behaviour towards legislation (ELI) and time (T).

The accumulation of customer return at time $t, t \in [0, T_1]$ can be formulated as following:

$$Q_{r0}(t) = Q_0\left(a_1 + Tanh\left(2T_1 * ELI_1^{T_1}\right)(1-a_1)\right)Tanh\left(t\left(\frac{t}{1+t}\right)^{T_1}\right) \quad (4.4)$$

Where Q_0 is the used products existing at time $t=0$, a_1 is the green awareness during the first time period, ELI_1 is the environmental legislative index during the first time period. $a_1 + Tanh\left(2T_1 * ELI_1^{T_1}\right)(1-a_1)$ represents the return percentage which is mainly determined by green awareness and legislation enforcement. However, legislative enforcement cannot impact customer return behaviour straight away. It influences customers throughout its time of implementation (i.e. T_1, which is also a product life span) following a S-shape trend.

The accumulation of customer return at time $t, t \in [T_1, T_2]$ can be formulated as follows:

$$Q_{r1}(t) = Q_{ru}(t) + Q_{re}(t) \quad (4.5)$$

Where $Q_{ru}(t)$ is the customer return accumulation of non-energy-efficient products at time t; $Q_{re}(t)$ is the customer return accumulation of energy-efficient products at time t. They are given by

$$Q_{ru}(t) = \left(\beta - \left(\frac{a_1 + ELI_1}{2}\right)^2\right) Q\,Tanh\left((t-PLC)\left(\frac{t-PLC}{1+t-PLC}\right)^{PLC}\right) * \left(a_2 + (1-a_2)Tanh\left(2(T_2-T_1)ELI_2^{(T_2-T_1)}\right)\right) * Tanh\left((t-PLC)\left(\frac{t-PLC}{1+t-PLC}\right)^{PLC}\right) \quad (4.6)$$

$$Q_{re}(t) = \left(1-\beta+\left(\frac{a_1+ELI_1}{2}\right)^2\right) Q\,Tanh\left(\left(t-PLC\right)\left(\frac{t-PLC}{1+t-PLC}\right)^{PLC}\right)* \\ \left(a_2+\left(1-a_2\right)Tanh\left(2\left(T_2-T_1\right)ELI_2^{(T_2-T_1)}\right)\right)* \\ Tanh\left(\left(t-PLC\right)\left(\frac{t-PLC}{1+t-PLC}\right)^{PLC}\right) \tag{4.7}$$

Where β is a percentage of demand for non-energy-efficient products, a_2 is the customer green awareness during the second time period, ELI_2 is the environmental legislative index during the second time period. β is determined by different prices of two types of products (i.e. energy-efficient and non energy-efficient products), the more expensive the products, the less would be demanded by customers, so β can be interpreted by $\beta = \frac{P_e}{P_e + P_u}$, where P_e is the price of an energy-efficient product, P_u is the price of a non-energy efficient product.

4.3.2 Modelling customer demand behaviour

Customers are able to purchase either energy-efficient products or non-energy-efficient products as they wish, so there are two types of customer demand accordingly, i.e. demand for energy-efficient products and demand for non-energy-efficient product.. There is price differentiation between these two types of products. Price differentiation determines demand percentages for each of the two products. Besides, subsidy towards energy-efficient products' purchased would affect customer purchasing, as the subsidy can be seen as a price/purchase cost deduction. Moreover, customer demand is a function of time, as the growth of customer demand follows the S-shape growth, i.e. the 5-phase PLC, as shown in Figure 8.

Customer demand only happens during the PLC, at time $t, t \in [0, PLC]$, it can be described by two variables, $Q_{DU}(t)$ and $Q_{DE}(t)$, both are functions of time, as shown in Equation (4.8):

$$Q_D(t) = Q_{DU}(t) + Q_{DE}(t) \tag{4.8}$$

Where $Q_{DU}(t)$ stands for the accumulation of demand for non-energy-efficient products, and $Q_{DE}(t)$ stands for the accumulation of demand for energy-efficient products. $Q_{DU}(t)$ can be formulated as:

$$Q_{DU}(t) = Q_{Du}(t) + Q_{du}(t) \tag{4.9}$$

Where $Q_{Du}(t)$ stands for the accumulation of demand for non-energy-efficient products when there is no incentive. Where $Q_{du}(t)$ stands for the additional accumulative demand for non-energy-efficient products with incentives taken into account (i.e. during stage 1 no matter what type of product a customer chooses to purchase he will get a return subsidy as long as he chooses to return the product through an authorised channel).

$$Q_{Du}(t) = \beta Q \, Tanh\left(t\left(\frac{t}{1+t}\right)^{PLC}\right) \tag{4.10}$$

$$Q_{du}(t) = Q_{r0}(t)\left(\beta - \left(\frac{a_1 + ELI_1}{2}\right)^2 - ELI_2{}^2\right) Tanh\left(2T_1 \times ELI_1^{PLC}\right) Tanh\left(t\left(\frac{t}{1+t}\right)^{PLC}\right) \tag{4.11}$$

Similarly, $Q_{DE}(t)$ can be formulated as:

$$Q_{DE}(t) = Q_{De}(t) + Q_{de}(t) \tag{4.12}$$

Where Q_{De} stands for the accumulation of demand (no incentive) for energy-efficient products, Q_{de} stands for the accumulation of additional demand (with incentive) for energy-efficient products. Q_{De} and Q_{de} can be formulated as:

$$Q_{De}(t) = (1-\beta) \times Q \times Tanh\left(t\left(\frac{t}{1+t}\right)^{PLC}\right) \tag{4.13}$$

$$Q_{de}(t) = Q_{r0}(t)\left(1-\beta+\left(\frac{a_1+ELI_1}{2}\right)^2 + ELI_2{}^2\right)Tanh\left(2T_1 \times ELI_1^{PLC}\right)Tanh\left(t\left(\frac{t}{1+t}\right)^{PLC}\right) \tag{4.14}$$

4.4 Model analysis

4.4.1 Forecasting customer return

Customer return during the whole modelling process can be seen as a 2-stage action. During the first stage, customers return their prior owned used products. During the second stage, customers return their EOL products purchased and owned during the first stage.

For this research, two types of customer returns are examined individually. In order to compare and contrast customer return behaviour at different legislative enforcement and different customer green awareness, the following conditions are applied:

(1) Legislative enforcement during the first stage and time span are two fixed parameters;

(2) Green awareness and legislative enforcement during the second stage are two control variables in each case;

(3) Control variables are manipulated at different levels to examine the model outcomes;

(4) The pattern/trend of accumulated customer return over a time span is examined;

(5) The trends of customer return are analysed separately within the two stages.

In the first stage:

It intends a product to be in the marketplace for a period time of 8 (its life span). During this period, customers are encouraged to return their EOL products to authorised recyclers by government through legislative enforcement. Also their green awareness influences their return behaviour at the same time. It examines how customer return behaviour will be under different combinations of customer green awareness and legislative enforcement over a PLC.

When customer green awareness is low (i.e. $a_1 \in (0, 0.25]$), the return behaviour pattern under differing ELI over a PLC is as follows:

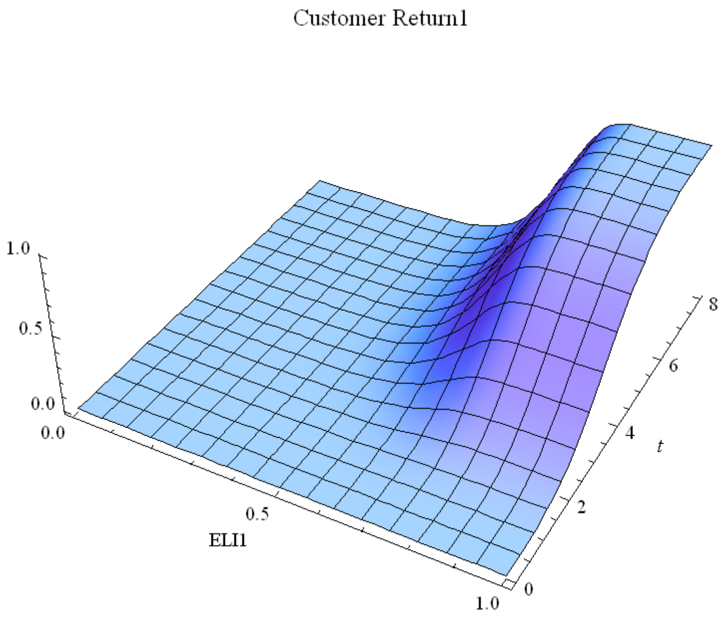


Figure 9. Customer return affected by a low green awareness

When customers have an intermediate green awareness $a_1 \in (0.25, 0.75]$, the return behaviour pattern under differing ELI over a PLC is:

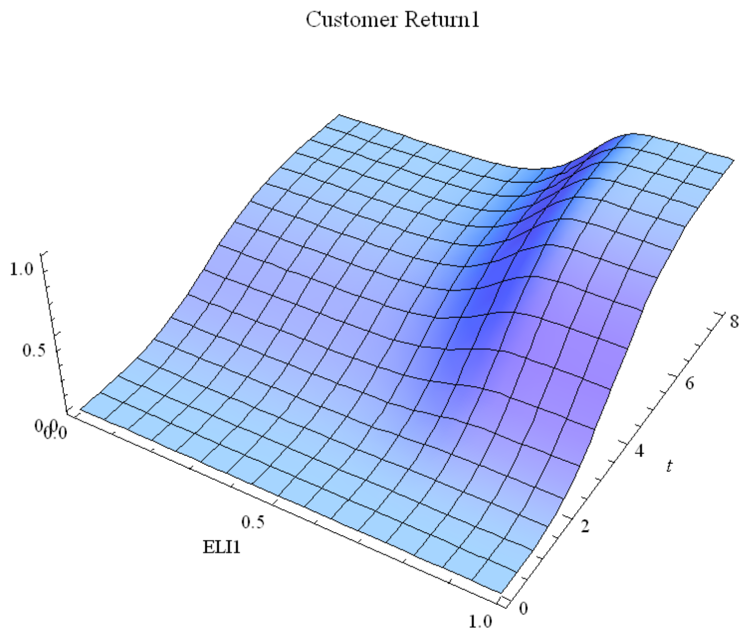


Figure 10. Customer return affected by an intermediate green awareness

When customers have a high green awareness $a_1 \in (0.75, 1]$, the return behaviour pattern under differing ELI over a PLC is :

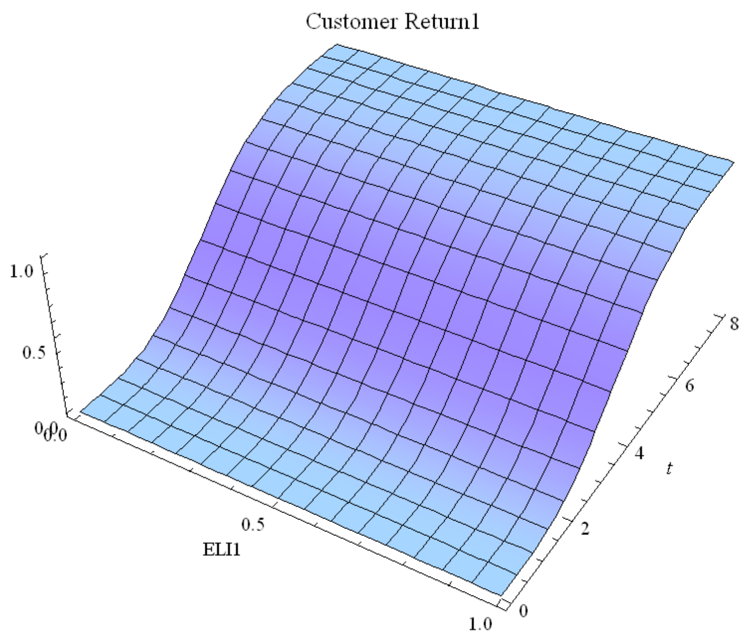


Figure 11. Customer return affected by a high green awareness

Customer return is affected by time, legislative enforcement and customer green awareness within this stage. Time can only affect customer return under the power of legislative enforcement and/or customer green awareness. The combined influence of legislative enforcement and customer green awareness determines the maximum accumulated customer returns at the end of stage 1(i.e. when $t = 8$. The pattern of customer return over this time span follows a S-shape growth, unless when there is no combined influence of customer green awareness and legislative enforcement, where there is no customer return at any time (see Figure 9). The pattern of customer return when legislative enforcement increases is also a S-shape growth. However, the impact of the same strength of legislative enforcement towards customer return becomes less and less when customer green awareness is strong enough to motivate customers to return their used products (see Figure 11).

In the second stage:

We intend the legislation to be in place during stage 2. During this period, customers are encouraged to return their EOL products purchased during stage 1 to authorised recyclers by government through legislative enforcement (ELI_2) , and their green awareness influences their return behaviour at the same time. We examine how customer return behaviour will be under different combinations of customer green awareness and legislative enforcement in time period 2 (i.e. $t \in [8,16]$). Also we consider the influence of legislation and green awareness on customer return from stage 1, as this determines the starting point of the accumulated return of stage 2 (i.e. when $t = 8$). Three extreme scenarios are examined as: (1) there is no green awareness in stage 1, and the combined strength of legislative enforcement and green awareness in stage 2 is none;(see Figure 12.) (2) there is no green awareness in either stage, but the combined strength of legislative enforcement and green awareness in stage 2 is maximum (i.e. $ELI_2 \, or \, a_2$ is 1); (see Figure 13.) (3) the green awareness in stage

1 and combined strength of legislative enforcement and green awareness in stage 2 are maximum (i.e. $a_1 = 1 \ \ ELI_2 \, or \, a_2$ is 1) (see Figure 14).

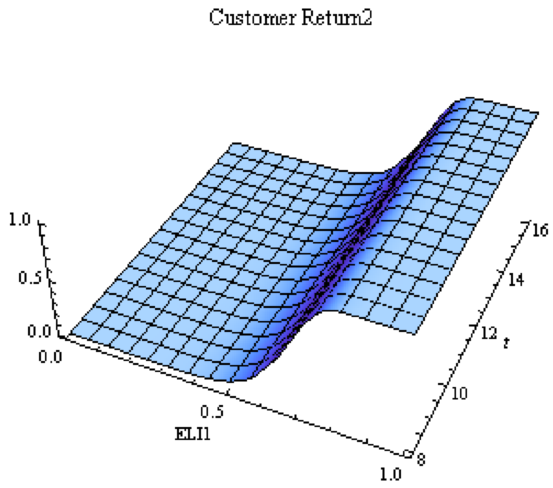


Figure 12. Customer return in stage 2 (1)

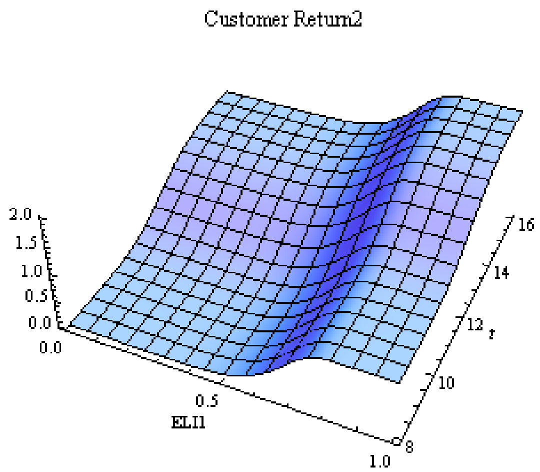


Figure 13. Customer return in stage 2 (2)

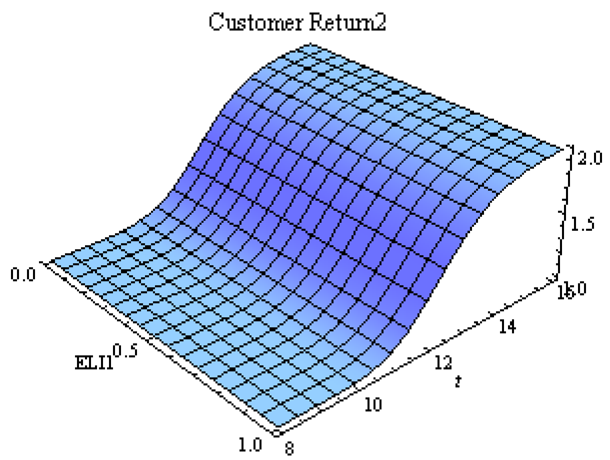


Figure 14. Customer return in stage 2 (3)

Customer return is affected by time, legislative enforcement (during both stages) and customer green awareness (during both stages). Time only affects customer return during this stage if there is a combined influence of legislative enforcement and customers green awareness. The combined influence of legislative enforcement and green awareness in the first stage determines the initial customer return of the second stage; the combined influence of legislative enforcement and green awareness in the second stage determines the final customer return at the end of the second stage. Between green awareness and legislative enforcement, the former has a stronger impact on customer return growth than the latter, especially when the combined influence of both factors is low, the improvement of green awareness will largely motivate customer return. However, this impact becomes weaker and weaker when the combined impact towards customer return is already strong. In general, the trend of customer return within this stage exhibits a S-shape growth when there is customer green awareness and legislative enforcement.

4.4.2 Forecasting customer demand

Customer demand includes two types of products, i.e. demand for energy-efficient products and demand for energy-inefficient product. Customer demand for both types of products only exists within a PLC time span.

For this research, two types of product demands are compared and contrasted to evaluate the impact of different green awareness and legislative enforcement at different stages, and price differentiation (mentioned in 4.3.1). The following conditions are applied within the analysis:

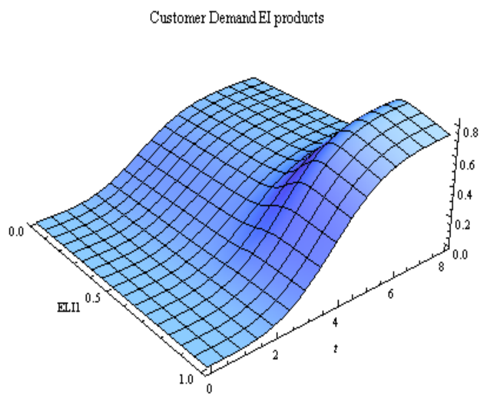
(1) Customer demand for both products is affected by legislative enforcement, green awareness, and time;

(2) Legislative enforcement during the second stage can be predicted (i.e. most of the legislation will affect a long period of time) and affects customer demand through price adjustment (subsidy of return);

(3) Green awareness within the second stage has no impact on customer purchase/demand during the first stage, and cannot be predicted;

(4) Demand percentages for the two products are determined by price differentiation between them.

The following two figures show the demand patterns towards energy-inefficient products (Figure 15.) and towards energy-efficient products (Figure 16.), at differing combined influence of legislative enforcement and green awareness, providing there is no price differentiation between the two types of products.



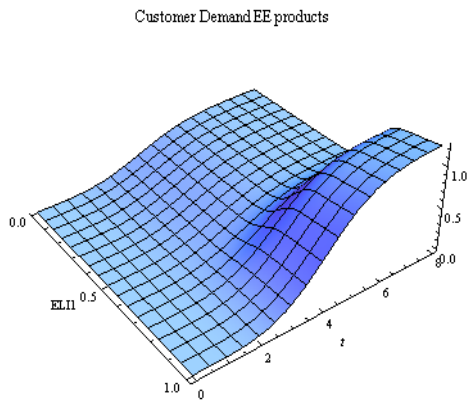


Figure 15. Customer demand for energy-inefficient products

Figure 16. Customer demand for energy-efficient products

Customer demand for either product includes general demand (the demand only caused by price change) and motivated demand (the demand caused by factors other than price change). The former exhibits an S-shape growth within a given time span and changes when price changes. The pattern of the latter is affected by:

(1) Customer green awareness. The increase of customer green awareness improves customer demand for energy-efficient products.

(2) Legislative enforcement. Legislative enforcement within the first stage directly improves customer demand for energy-efficient products; legislative enforcement within the first stage improves customer demand for energy-efficient products through subsidy. However, the subsidy has a time lag. Its inertia leads to a lesser influence on customer demand for energy-efficient products within the first stage.

(3) Price differentiation. Price has an important role as a determiner of customer demand. However, price differentiation has no influence when both/either customers and/or government act(s) as a stronger role than price in purchasing.

(4) Time. Inertia in customer purchasing behaviour.

4.5 Summary

Customer behaviour plays a critical role in both RL and CLSC. Customer return is the starting point of a RL operation. Customer return behaviour including when and how many customers return their EOL products affect a MRR bond's decision on how to collect and process returned products. Customer return behaviour is uncertain, so understanding it can help (re-)manufacturers make better decisions on processing the returned products. In a CLSC, customer demand is a trigger of product manufacturing, hence it affects all activities throughout the whole supply chain. Together with customer return, in terms of customer behaviour towards EOL products, both customer green awareness and government legislation have strong impact on customer demand and customer return.

The research presented in this chapter focuses on customer return and demand behaviours. The purpose of it is to analyse the impact of legislative enforcement and customer awareness toward the return and demand behaviours. The models established quantify parameters which are seen as qualitative parameters by most SC research, i.e. legislative enforcement and green awareness. It analyses the above behaviours within a PLC time span, in different situations, i.e. a mix of different levels of legislative enforcement and green awareness.

In order to encourage customer green behaviour (return and demand), strengthening legislative enforcement helps to improve customer EOL product return directly, and encourage customer demand for energy-efficient products through subsidy. However, legislative enforcement has to work with customers' own green awareness to maximize its effect and has less impact than customer green awareness on customer EOL product return when the combined influence of them is low. Especially, when government tries to promote customer demand for products through subsidy leverage as the inertia delays its impact. Price differentiation works as an important determination of customer demand when there are no other factors affecting customer demand. Differentiated price has reducing impact on customer demand when customers have a strong willingness to purchase energy-efficient products and/or government enforces relevant purchase behaviours.

Chapter 5. Forecasting product returns for remanufacturing: An advanced GERT approach

5.1 Introduction

Products return forecasting has been identified as one of the most complicated issues in CLSC research, which has been reviewed in Chapter 2. An accurate forecast facilitates profitability for a CLSC. This is because it enables better manage capacity, remanufacturing schedules, timing, inventory, resourcing allocation and many other activities. Research objective 3 is to develop an appropriate approach that can be used to forecast returns. This approach must be capable of capturing the stochastic characteristics in terms of return probability and timing in the dynamic process of products return. For this reason, we adopt the Graphical Evaluation and Review Technique (GERT) which can reflect the RL network topology and dynamics. We advance GERT by introducing Mason's rules (Mason, 1956) in order to derive an analytic result of forecasting in a network that has feedback loops, i.e. products can be reused more than once. Furthermore, the advanced GERT also considers product structure to allow predicting of the amount and time of detachable parts. Therefore, it can be implemented in any type of network and product structure provided the Bill of Material (BOM) is known.

Figure 17 highlights chapter 5 in the structure of the thesis.

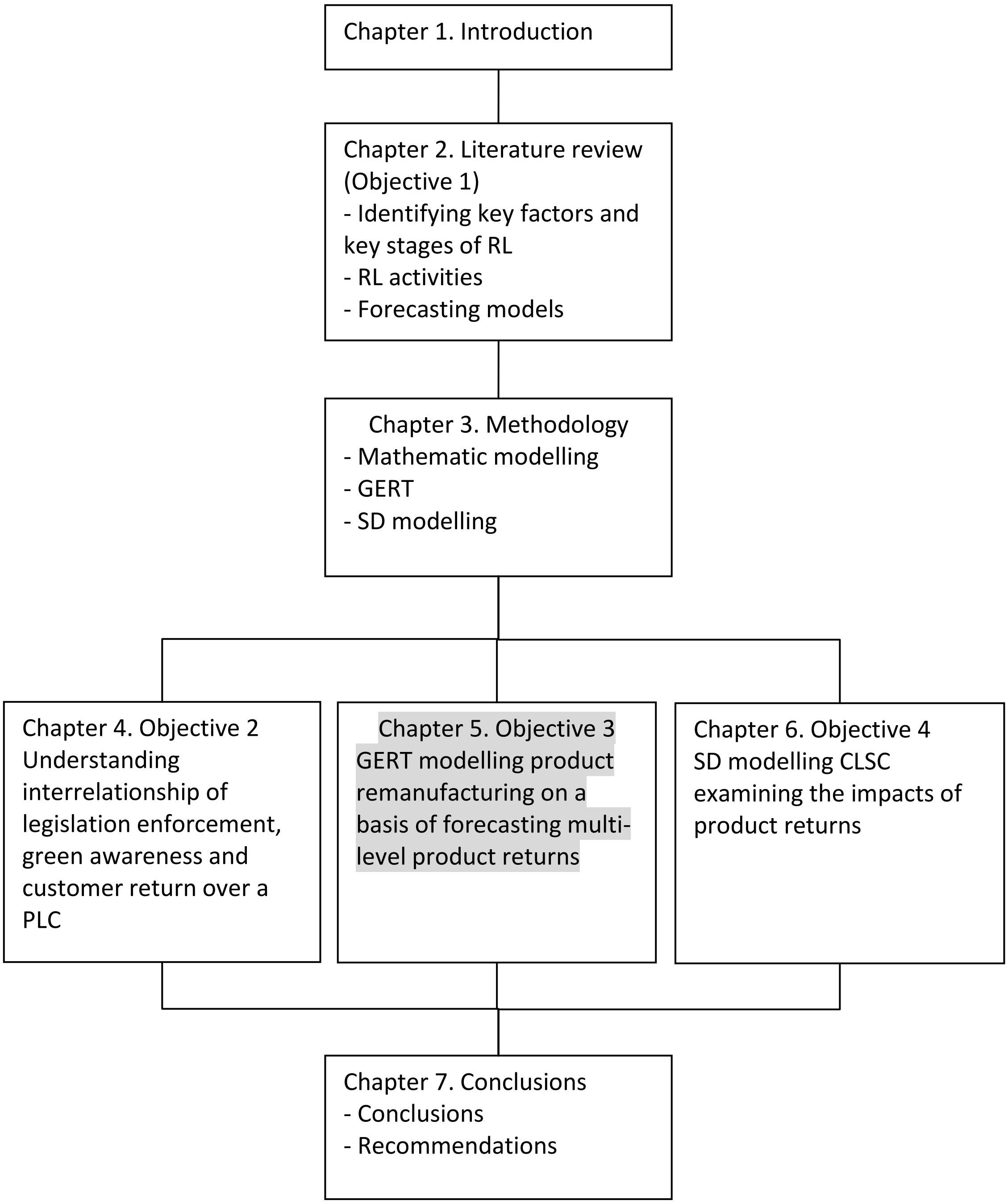


Figure 17. Flow chart of the thesis structure focused on Objective 3 (Source: author)

5.2 A recap of advanced GERT approach and its application

The inputs of the GERT are the parameters for each activity. These parameters include: the probability from activity (node) i to activity (node) j, estimated time period for each activity and the product's original component structure. In this case, the outputs are the prediction of product return quantity, timing and probability, salvageable parts/components/materials' quantity, and finally disposal.

To generalise and also simplify the process, the methodology can be described in eight steps:

Step 1: Mapping the process in order to derive the causal flow chart;

Step 2: Translating the flow chart into the stochastic network;

Step 3: Estimating each activity's parameters (from node i to node j): probability P_{ij} and time probability density function $f(t_i)$;

Step 4: Integrating the two parameters of each activity (i,j) into one transfer function $w_{ij}(s)$: $w_{ij}(s) = P_{ij} M_{ij}(s)$

Where $M_{ij}(s) = E(e^{t_i s}) = \int_{-\infty}^{+\infty} e^{t_i s} f(t_i) dt_i$ is a moment-generating function (MGF).

Step 5: Applying Mason's rules (Mason 1956) - details explained in 4.4.2 - calculate total equivalence transfer function $W_{E_{0n}}$ from initial node 0 to node j based on the network structure and the value of $w_{ij}(s)$. This is a rather complex calculation but indeed a key stage;

Step 6: According to the definition of MGF, the probability ($P_{E_{0j}}$) of the activity from initial node 0 to j is $P_{E_{0j}} = W_{E_{0j}}(s)\big|_{s=0}$;

Step 7: According to the characteristics of MGF (Pishro-Nik, 2014, pp.324-329), the expected return time from initial node 0 to node j is:

$$E(t) = \mu_1 = \frac{\partial}{\partial s}[M_{E_{0n}}(s)]|_{s=0} = \frac{1}{P_{E_{0n}}}\frac{\partial}{\partial s}[W_{E_{0n}}(s)]|_{s=0};$$

Step 8: The predicted quantity of product return/parts/components/materials equals to the probability of each activity multiplied by total amount of sold product: $P_{E_{0j}} \times Sales$.

In the following section, further details on how to calculate each activity and the desired outcomes are provided.

5.3 Analysis of GERT remanufacturing networks

5.3.1 Mapping the process of product return and remanufacturing

As shown in Figure 18, when a consumer receives a product, if he/she is not satisfied with the product it can be returned to the retailer. The returned products will be tested and classified into directly resellable or reconditionable and for sale back to the first-hand market. This is a common practice with mobile phones and laptops, for instance refurbished Apple Macs; there might be some products going to the second-hand market at a lower price. In this research, to simplify the case, we assume that retailers are involved in both first- and second-hand markets. If a product is not resellable, it will be sent to a remanufacturer to undertake sorting and testing. Based on return quality, remanufacturing processes include: (a) disassembling product into parts, reconditioning and resale; (b) disassembling parts into components, reconditioning and resale; (c) extracting useful materials from components and sale to a material market; and (d) disposal.

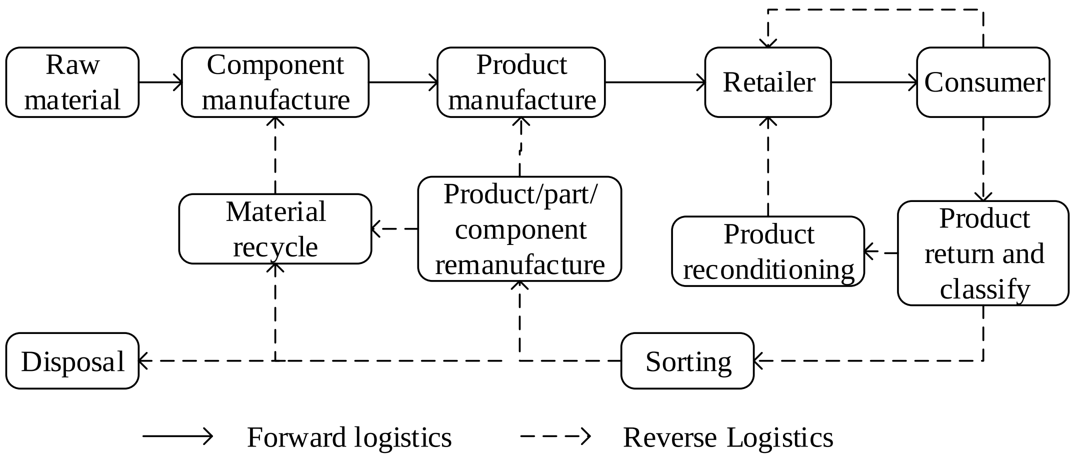


Figure 18. Closed-loop manufacturing and remanufacturing process

5.3.2 GERT stochastic network

In a GERT network, each node is represented by a different icon. In inputs, there are three types of relationship: XOR, OR and AND. Outputs have two types of relationships: non-deterministic and deterministic. By combining input and output, there are six logic nodes, as shown in Table 5. In the GERT network, a line with an arrow means a job and each line has two parameters: probability, which means the possibility of doing the job; and time, which means the duration of the job. The network for product return and remanufacturing is shown in Figure 19. For each node i, the process can be classified as three types, the distribution times of which are:

Activity1: sales from a new product launch to exit market. We assume that the process time obeys a normal distribution N (μ, σ^2), which reflects the curve of the PLC.

Activity2: multiple uses of products. It assumes that the multiple usage time μ_i is a negative exponential distribution given the fact that it is in correlation with product breakdowns (Christer & Waller, 2015; Fu et al., 2015; Ke & Wang, 1999, Taylor & Andrushchenko, 2014).

Activity 3: remanufacturing-related activities include sorting, testing, dismantling and so on. Without loss of generosity, to simplify the mathematical process, it assumes that the process time t_i is a constant (Xie et al., 2007).

The parameter P_{ij} refers to the probability of state *i* transitioning to state *j* with the value of a *P*. The superscripts *p*, *c* and *m* mean that the product can be dismantled into a number of *p* parts, *c* components and *m* types of materials, respectively.

Table 5. Logic nodes for GERT

Input/output	Deterministic	Non-deterministic
XOR		
OR		
AND		

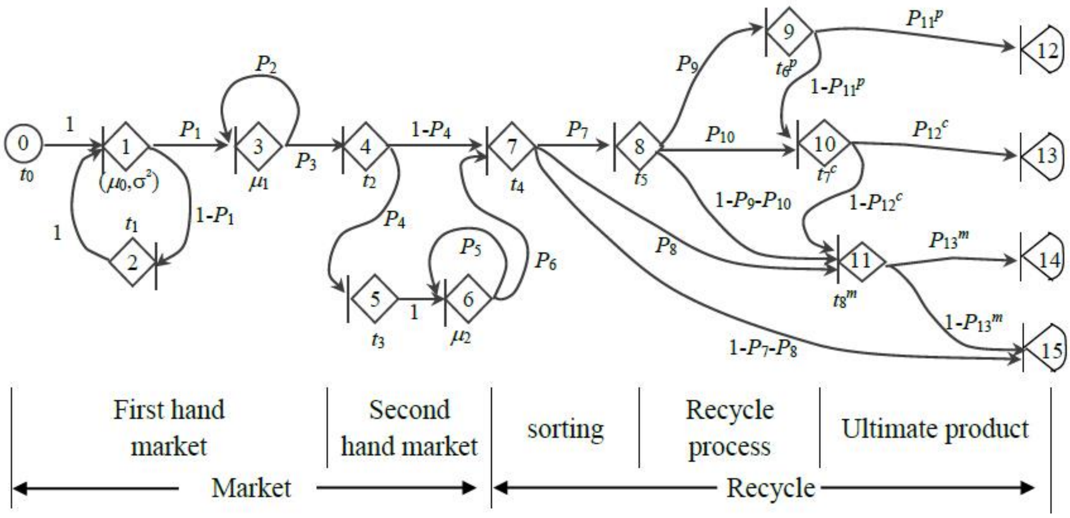


Figure 19. Product recycling diagram

5.3.3 Notation

The description of each node is shown Table 6:

Table 6. Node description

Node	Indication
0	Company manufactures the products
1	First-hand market
2	Goods returned without use
3	Product in use in first-hand market
4	Used product sorting
5	Second-hand market including refurbishment
6	Product in use in second-hand market
7	Classifying products
8	Product disassembly
9	Parts refurbishment
10	Component refurbishment
11	Recycling for materials
12	Refurbished parts inventory
13	Refurbished components inventory
14	Recycled material inventory
15	Disposal

The transition process is shown in Table 7.

Table 7. Arrow indication for each process

Arrow	Indication	Probability of P_{ij}
0→1	Product to first-hand market	100%
1→2	Product return from the consumer	1- P_1
2→1	Return product to the retailer	100%
1→3	Product sold to the customer in use	P_1
3→3	Multiple uses by customer in first-hand market	P_2
3→4	Product enters the sorting point	P_3
4→5	Refurbishment	P_4
4→7	Product cannot be refurbished and enters product sorting and testing point	1-P_4
5→6	Sold to the customer in second-hand market	100%
6→6	Multiple uses by customer in second-hand market	P_5
6→7	Product enters product sorting and testing point	P_6
7→8	Product enters dismantling point	P_7

7→11	Product goes to material extracting process	P_8
7→15	Disposal	$1-P_7-P_8$
8→9	Enter parts refurbishment process	P_9
8→10	Enter component remanufacturing process	P_{10}
8→11	Enter material extracting process	$1- P_9 – P_{10}$
9→10	Part refurbishment fails so goes to component remanufacturing process	$1 - P_{11}^{p}$
9→12	Enter the parts inventory	P_{11}^{p}
10→11	Refurbishment fails so goes to material extracting process	$1 - P_{12}^{c}$
10→13	Enter component inventory	P_{12}^{c}
11→14	Enter material inventory	P_{13}^{m}
11→15	Disposal	$1 - P_{13}^{m}$

5.3.4 Moment-Generating function (MGF)

The Moment-Generating Function (MGF) is used to describe a random variable's probability distribution as an alternative specification. Compared with the cumulative distribution function (CDF) or probability density function (PDF), MGF offers a different method of analysing results through the weighted sum of random variables (Wikipedia). The MGF of a random variable *t* is defined:

$$M_t(s) = E(e^{ts}), \quad s \in R \tag{5.1}$$

wherever this expectation exists.

In the product return and remanufacturing (PRR) network, assuming that the density function is continuous and the completion time's density function at node *i* is $f(t_i)$, then the MGF of t_i is the MGF of the arrow from *i* to *j*, which is

$$M_{ij}(s) = E(e^{t_i s}) = \int_{-\infty}^{+\infty} e^{t_i s} f(t_i) dt_i \tag{5.2}$$

If t_i is constant, the MGF is

$$M_{ij}(s) = e^{t_i s} \tag{5.3}$$

If t_i obeys a negative exponential distribution, the MGF is

$$M_{ij}(s) = \frac{1}{1 - \mu_i s} \tag{5.4}$$

While if t_i obeys the normal distribution $N(\mu, \sigma^2)$, the MGF is

$$M_{ij}(s) = e^{\mu_i s + \frac{1}{2}\sigma^2 s^2} \tag{5.5}$$

5.3.5 Mason equivalence principle

The equivalence transfer function from any node *i* to node *j* can be obtained by using Mason's rules (Mason, 1956):

$$W_{E_{ij}}(s) = \frac{\sum_{l=1}^{n} G_l \Delta_l}{\Delta} \tag{5.6}$$

Where G_l is the gain of the l^{th} forward route from *i* to *j*, and Δ_l is the loop gain of the l^{th} loop, $l \in \{1, n\}$, and must be an integer. In control theory, 'gain' means the path or loop's transfer function i.e. output is divided by input.

Δ is the determinant of the graph, where

$$\Delta = 1 - \sum L_x + \sum L_x L_y - \sum L_x L_y L_z + \ldots + (-1)^k \sum \ldots + \ldots \tag{5.7}$$

Where L refers to a loop, $\sum L_x$ is the sum of the transfer coefficient for different loops, $\sum L_x L_y$ is sum of the transfer coefficient for two non-touch loops, $\sum L_x L_y L_z$ is the sum of the transfer coefficient for three non-touch loops, $(-1)^k \sum \ldots$ is sum of the transfer coefficient for *k* non-touch loops....;

5.3.6 Transfer functions for the product recycling process

The process must account from initial node 0. Through using (5.3), (5.4) and (5.5), the MGFs for each state transition are

$$M_{01}(s) = e^{t_0 s} \qquad M_{12}(s) = M_{13}(s) = e^{\mu_0 s + \frac{1}{2}\sigma^2 s^2}$$

$$M_{21}(s) = e^{t_1 s} \qquad M_{33}(s) = M_{34}(s) = \frac{1}{1 - \mu_1 s}$$

$$M_{45}(s) = M_{47}(s) = e^{t_2 s} \qquad M_{56}(s) = e^{t_3 s}$$

$$M_{66}(s) = M_{67}(s) = \frac{1}{1-\mu_2 s} \qquad M_{78}(s) = M_{7,11}(s) = M_{7,15}(s) = e^{t_4 s}$$

$$M_{89}(s) = M_{8,10}(s) = M_{8,11}(s) = e^{t_5 s} \qquad M^{p}_{9,10}(s) = M^{p}_{9,12}(s) = e^{t_6^p s}$$

$$M^{c}_{10,11}(s) = M^{c}_{10,13}(s) = e^{t_7^c s} \qquad M^{m}_{11,14}(s) = M^{m}_{11,15}(s) = e^{t_8^m s}$$

The transfer function for arrow (*i, j*) is described below:

$$w_{ij}(s) = P_{ij} M_{ij}(s) \tag{5.8}$$

Therefore, the transfer function for each state transition is

$$w_{01}(s) = e^{t_0 s} \qquad w_{12}(s) = (1-P_1)e^{\mu_0 s + \frac{1}{2}\sigma^2 s^2} \qquad w_{13}(s) = P_1 e^{\mu_0 s + \frac{1}{2}\sigma^2 s^2}$$

$$w_{21}(s) = e^{t_1 s} \qquad w_{33}(s) = \frac{P_2}{1-\mu_1 s} \qquad w_{34}(s) = \frac{P_3}{1-\mu_1 s}$$

$$w_{45}(s) = P_4 e^{t_2 s} \qquad w_{47}(s) = (1-P_4)e^{t_2 s} \qquad w_{56}(s) = e^{t_3 s}$$

$$w_{66}(s) = \frac{P_5}{1-\mu_2 s} \qquad w_{67}(s) = \frac{P_6}{1-\mu_2 s} \qquad w_{78}(s) = P_7 e^{t_4 s}$$

$$w_{7,11}(s) = P_8 e^{t_4 s} \qquad w_{7,15}(s) = (1-P_7-P_8)e^{t_4 s} \qquad w_{89}(s) = P_9 e^{t_5 s}$$

$$w_{8,10}(s) = P_{10} e^{t_5 s} \qquad w_{8,11}(s) = (1-P_9-P_{10})e^{t_5 s} \qquad w^{p}_{9,10}(s) = (1-P^{p}_{11})e^{t_6^p s}$$

$$w^{p}_{9,12}(s) = P^{p}_{11} e^{t_6^p s} \qquad w^{c}_{10,11}(s) = (1-P^{c}_{12})e^{t_7^c s} \qquad w^{c}_{10,13}(s) = P^{c}_{12} e^{t_7^c s}$$

$$w^{m}_{11,14}(s) = P^{m}_{13} e^{t_8^m s} \qquad w^{m}_{11,15}(s) = (1-P^{m}_{13})e^{t_8^m s}$$

5.3.7 Forecasting product return

From state 0 to state 7, there are 2 paths, which are 0→1→3→4→7 and 0→1→3→4→5→6→7. Its characteristic formula is

$$\begin{aligned}\Delta &= 1 - w_{12}w_{21} - w_{33} - w_{66} + w_{12}w_{21}w_{33} + w_{12}w_{21}w_{66} + w_{33}w_{66} - w_{12}w_{21}w_{33}w_{66} \\ &= (1-w_{12}w_{21})(1-w_{33})(1-w_{66})\end{aligned} \tag{5.9}$$

and by using (5.6) for simplification, the equivalence transfer function is

$$\begin{aligned}W_{E_{07}}(s) &= \frac{w_{01}\left(w_{13}w_{34}w_{47}(1-w_{66}) + w_{13}w_{34}w_{45}w_{56}w_{67}\right)}{(1-w_{12}w_{21})(1-w_{33})(1-w_{66})} \\ &= \frac{w_{01}}{(1-w_{12}w_{21})} \cdot \frac{w_{13}w_{34}}{(1-w_{33})} \cdot \left(w_{47} + \frac{w_{45}w_{56}w_{67}}{(1-w_{66})} \right) \\ &= \frac{e^{t_0 s}}{(1-(1-P_1)e^{t_1 s + \mu_0 s + \sigma^2 s^2/2})} \cdot \frac{P_1 P_3 e^{\mu_0 s + \sigma^2 s^2/2}}{(1-\mu_1 s - P_2)} \cdot \left((1-P_4)e^{t_2 s} + \frac{P_4 P_6 e^{(t_2+t_3)s}}{(1-\mu_2 s - P_5)} \right) \\ &= \frac{P_1 P_3 e^{t_0 s + \mu_0 s + \sigma^2 s^2/2}}{(1-(1-P_1)e^{t_1 s + \mu_0 s + \sigma^2 s^2/2})(1-\mu_1 s - P_2)} \cdot \left((1-P_4)e^{t_2 s} + \frac{P_4 P_6 e^{(t_2+t_3)s}}{(1-\mu_2 s - P_5)} \right)\end{aligned} \tag{5.10}$$

Let $s=0$, $W_{E_{0j}}(0) = P_{E_{0j}} M_{Ej}(0) = P_{E_{0j}} \int_{-\infty}^{+\infty} e^{ts} f(t)dt \,|_{s=0} = P_{E_{0j}}$ and the expected time from 0 to *j* is the first-order derivation of MGF.

Therefore, the probability of product return is

$$\mathrm{P}_{E_{07}} = \frac{P_3}{(1-P_2)} \cdot \left((1-P_4) + \frac{P_4 P_6}{(1-P_5)} \right) \tag{5.11}$$

With the expected time:

$$t_{E_{0n}} = E(t) = \frac{\partial}{\partial s}\left[M_{E_{0n}}(s) \right]\bigg|_{s=0} = \frac{1}{P_{E_{0n}}} \frac{\partial}{\partial s}\left[W_{E_{0n}}(s) \right]\bigg|_{s=0} \tag{5.12}$$

Theorem: For the probability at each stage in the network, it must be in the range of $[0,1]$.

Proof.

$$Let\ P_2 + P_3 \le 1, \text{ where } P_2\ and\ P_3 \ge 0, \text{ therefore } P_3 \le (1-P_2);$$

$$
\begin{aligned}
&\left((1-P_4)+\frac{P_4P_6}{(1-P_5)}\right)=\frac{(1-P_5)-P_4(1-P_5-P_6)}{(1-P_5)}\\
&\text{where}\quad 0\le(1-P_5-P_6)\le 1,\ \text{and}\ 0\le P_4\le 1,\\
&\text{therefore}\quad 0\le P_4(1-P_5-P_6)\le 1;\\
&\text{then}\ \ (1-P_5)-P_4(1-P_5-P_6)\le(1-P_5);\\
&\text{therefore}\ \frac{P_3}{(1-P_2)}\cdot\left((1-P_4)+\frac{P_4P_6}{(1-P_5)}\right)\le 1
\end{aligned}
\quad . \tag{5.13}
$$

The expected time of product return is:

$$
\left.\frac{\partial}{\partial s}W_{E_{07}}(s)\right|_{s=0}=\frac{P_3\begin{pmatrix}P_1(1-P_2)(1-P_5)\left(1-P_5+P_4(-1+P_5+P_6)\right)t_0\\+(1-P_1)(1-P_2)(1-P_5)\left(1-P_5+P_4(-1+P_5+P_6)\right)(t_1+\mu_0)\\+P_1P_2(1-P_5)\left(1-P_5+P_4(-1+P_5+P_6)\right)\mu_1\\+P_1(1-P_2)P_5\left(1-P_5+P_4(-1+P_5+P_6)\right)\mu_2\\+P_1(1-P_2)(1-P_5)\\\begin{pmatrix}(-1+P_4)(-1+P_5)(t_2+\mu_0)+P_4P_6(t_2+t_3+\mu_0)\\+(-1+P_4)(-1+P_5)\mu_1+P_4P_6\mu_1+(-1+P_4)P_5\mu_2+P_4P_6\mu_2\end{pmatrix}\end{pmatrix}}{P_1(-1+P_2)^2(-1+P_5)^2} \tag{5.14}
$$

$$
\begin{aligned}
t_{E_{07}}&=\frac{1}{P_{E_{07}}}\frac{\partial}{\partial s}[W_{E_{07}}(s)]|_{s=0}\\
&=\begin{pmatrix}t_0+\left(\frac{1}{P_1}-1\right)t_1+\left(\frac{1}{P_1}-1\right)\mu_0-\frac{P_2\mu_1}{P_2-1}\\+\frac{\begin{pmatrix}(-1+P_5)\begin{pmatrix}\left(1-P_5+P_4(-1+P_5+P_6)\right)t_2-(-1+P_5)(\mu_0+\mu_1)\\+P_4\left((-1+P_5)(\mu_0+\mu_1)+P_6(t_3+\mu_0+\mu_1)\right)\end{pmatrix}\\-P_4P_6\mu_2\end{pmatrix}}{\left((-1+P_5)\left(1-P_5+P_4(-1+P_5+P_6)\right)\right)}\end{pmatrix}
\end{aligned} \tag{5.15}
$$

5.3.8 Forecasting remanufacture-able parts

From node 7 to node 12, which is the parts inventory, the equivalence transfer function is

$$
W^p_{E_{7,12}}(s)=w_{78}w_{89}w^p_{9,12}=e^{(t_4+t_5+t_6^p)s}P_7P_9P_{11}^p \tag{5.16}
$$

And the probability of remanufacturable parts p is

$$P_{E_{7,12}}^{p}=P_7P_9P_{11}^{p} \tag{5.17}$$

$$\text{Let } 0\le P_7,P_9,P_{11}^{p}\le 1;\quad \text{We have } 0\le P_7P_9P_{11}^{p}\le 1 \tag{5.18}$$

The expected recycling time is

$$t_{E_{7,12}}^{p}=t_4+t_5+t_6^{p} \tag{5.19}$$

If the quantity of returned product is q_w, the amount of p^{th} parts in each product's BOM is q_p, then the amount of remanufacturable p^{th} part is

$$Q_p=(P_{E_{07}}q_pP_{E_{7,12}}^{p})\cdot q_w=K_p\cdot q_w \tag{5.20}$$

Substituting (5.11) and (5.17) into (5.20), we have

$$K_p=\frac{P_3P_7P_9P_{11}^{p}}{(1-P_2)}\cdot\left((1-P_4)+\frac{P_4P_6}{(1-P_5)}\right)\cdot q_p \tag{5.21}$$

And the total remanufacturable part is

$$\sum_p Q_p=(\sum_p K_p)\cdot q_w=K_{parts}^{*}\cdot q_w \tag{5.22}$$

where K_{parts}^{*} means the remanufacturable parts in each product.

5.3.9 Forecasting remanufacturable components

Similarly, from node 7 to node 13, which is the component inventory, the equivalence transfer function is

$$W_{E_{7,13}}^{p,c}(s)=w_{78}(w_{89}w_{9,10}^{p}+w_{8,10})w_{10,13}^{c}=e^{(t_4+t_5+t_7^{c})s}P_7P_{12}^{c}(P_{10}+e^{t_6^{p}s}P_9(1-P_{11}^{p})) \tag{5.23}$$

and the probability of remanufacturable component c from part p with its recycling time expectation is

$$P_{E_{7,13}}^{p,c} = P_7 P_{12}^c (P_{10} + P_9(1 - P_{11}^p)) \tag{5.24}$$

Lemma 1. The probability from node 0 to 7 must be in the range of $[0, 1]$.

Proof.

Let $0 \le 1 - P_{11}^p \le 1$, we have $P_7 P_{12}^c (P_{10} + P_9(1 - P_{11}^p)) \le P_7 P_{12}^c (P_9 + P_{10})$;

We know $0 \le (P_9 + P_{10}) \le 1$ from node 8, therefore

$P_7 P_{12}^c (P_{10} + P_9(1 - P_{11}^p)) \le P_7 P_{12}^c$

Because $0 \le P_7 \le 1$, $0 \le P_{12}^c \le 1$,

We have $0 \le P_7 P_{12}^c (P_{10} + P_9(1 - P_{11}^p)) \le 1$

Therefore,

$$\frac{\partial}{\partial s} W_{E_{7,13}}^{p,c}(s)\Big|_{s=0} = P_7 P_{12}^c ((t_4 + t_5 + t_7^c)(P_{10} + P_9(1 - P_{11}^p)) + (t_6^p P_9 (1 - P_{11}^p)) \tag{5.25}$$

$$\begin{aligned} t_{E_{7,13}}^{p,c}(s) &= \frac{1}{P_{E_{7,13}}^{p,c}} \frac{\partial}{\partial s}[W_{E_{7,13}}^{p,c}(s)]|_{s=0} \\ &= \frac{P_7 P_{12}^c ((t_4 + t_5 + t_7^c)(P_{10} + P_9(1 - P_{11}^p)) + (t_6^p P_9 (1 - P_{11}^p))}{P_7 P_{12}^c (P_{10} + P_9(1 - P_{11}^p))} \\ &= \frac{P_{10}\left(t_4 + t_5 + t_7^c\right) + P_9\left(1 - P_{11}^p\right)\left(t_4 + t_5 + t_6^p + t_7^c\right)}{P_{10} + P_9 - P_{11}^p P_9} \\ &= t_4 + t_5 + t_6^p + t_7^c - \frac{P_{10} t_6^p}{P_{10} + P_9(1 - P_{11}^p)} \end{aligned} \tag{5.26}$$

If the quantity of product is q_w, the amount of the c^{th} component from the p^{th} part in each product is q_c^p, then the amount of the returned c^{th} component from the p^{th} part is:

$$Q_c^p = P_{E_{07}} q_p q_c^p P_{E_{7,13}}^{p,c} \cdot q_w = K_c^p \cdot q_w \tag{5.27}$$

Where

$$K_c^p = \frac{P_3}{(1-P_2)} \cdot \left((1-P_4) + \frac{P_4 P_6}{(1-P_5)} \right) P_7 P_{12}^c (P_{10} + P_9 (1-P_{11}^p)) q_p q_c^p \tag{5.28}$$

The total returned component is

$$\sum_c \sum_p Q_c^p = (\sum_c \sum_p K_c^p) \cdot q_w = K_{components}^* \cdot q_w \tag{5.29}$$

Where $K_{components}^*$ is the total remanufacturable component in each product.

5.3.10 Forecasting recyclable materials

Likewise, from node 7 to node 14, which is the material inventory, the equivalence transfer function is

$$\begin{aligned} W_{E_{7,14}}^{p,c,m}(s) &= (w_{7,11} + w_{78}(w_{8,11} + (w_{8,10} + w_{89} w_{9,10}^p) w_{10,11}^c)) w_{11,14}^m \\ &= \mathrm{e}^{s(t_4 + t_8^m)} (P_8 + P_7 \mathrm{e}^{st_5} ((1-P_9-P_{10}) + (P_{10} + P_9 (1-P_{11}^p) \mathrm{e}^{st_6^p})(1-P_{12}^c) \mathrm{e}^{st_7^c})) P_{13}^m \end{aligned} \tag{5.30}$$

The probability and time of material recycle for component i are

$$\begin{aligned} P_{E_{7,14}}^{p,c,m} &= (P_8 + P_7((1-P_9-P_{10}) + (P_{10} + P_9(1-P_{11}^p))(1-P_{12}^c))) P_{13}^m \\ &= (P_8 + P_7(1 - (P_9 + P_{10}) P_{12}^c - P_9 P_{11}^p (1-P_{12}^c))) P_{13}^m \\ &= \left(P_8 + P_7 \left(1 + P_9 P_{11}^p \left(P_{12}^c - 1\right) - P_{12}^c \left(P_{10} + P_9\right)\right)\right) P_{13}^m \end{aligned} \tag{5.31}$$

Lemma 2. The probability from node 7 to 17 must be in the range of $[0, 1]$.

Proof.

For $P_{E_{7,14}}^{p,c,m} = (P_8 + P_7((1-P_9-P_{10}) + (P_{10} + P_9(1-P_{11}^p))(1-P_{12}^c))) P_{13}^m$

Because $1 - P_9 - P_{10} \geq 0, (1-P_{11}^p) \geq 0, (1-P_{12}^c) \geq 0;\ P_8, P_7, P_{10}, P_9, P_{13}^m \geq 0$

Therefore $P_{E_{7,14}}^{p,c,m} \geq 0$

$$
\begin{aligned}
&\text{Because} \quad 0 \le (P_9 + P_{10}) \le 1 \\
&\text{We have} \quad P^{p,c,m}_{E_{7,14}} \le (P_8 + P_7(1 - P_9 P^p_{11}(1 - P^c_{12})))P^m_{13}; \\
&\text{Also,} \quad \text{because } P_9, P^p_{11} \ge 0, \ \text{ and } (1 - P^c_{12}) \ge 0, \\
&\qquad \text{We have } P^{p,c,m}_{E_{7,14}} \le (P_8 + P_7)P^m_{13}; \\
&\qquad \text{And} \quad 0 \le P_7, P_8, P^m_{13} \le 1, \\
&\text{Therefore,} \quad P^{p,c,m}_{E_{7,14}} \le 1.
\end{aligned} \tag{5.32}
$$

Hence, we have

$$
\frac{\partial}{\partial s} W^{p,c,m}_{E_{7,14}}(s)\bigg|_{s=0} = P^m_{13} \begin{pmatrix} P_8\left(t_4 + t^m_8\right) - P_7\left(-1 + P_{10} + P_9\right)\left(t_4 + t_5 + t^m_8\right) \\ -P_{10}\left(P^c_{12} - 1\right) \cdot P_7\left(t_4 + t_5 + t^c_7 + t^m_8\right) + \\ \left(P^p_{11} - 1\right)\left(P^c_{12} - 1\right) P_7 P_9 \left(t_4 + t_5 + t^p_6 + t^c_7 + t^m_8\right) \end{pmatrix} \tag{5.33}
$$

$$
\begin{aligned}
t^{p,c,m}_{E_{7,14}}(s) &= \frac{1}{P^{p,c,m}_{E_{7,14}}} \frac{\partial}{\partial s}[W^{p,c,m}_{E_{7,14}}(s)]\,|_{s=0} \\
&= \frac{\begin{pmatrix} P_8\left(t_4 + t^m_8\right) - P_7\left(P_{10} + P_9 - 1\right)\left(t_4 + t_5 + t^m_8\right) - \\ P_{10}\left(p^c_{12} - 1\right) P_7 \cdot \left(t_4 + t_5 + t^c_7 + t^m_8\right) + P\left(P^p_{11} - 1\right) \cdot \\ \left(P^c_{12} - 1\right) P_7 P_9 \left(t_4 + t_5 + t^p_6 + t^c_7 + t^m_8\right) \end{pmatrix}}{P_8 + P_7\left(1 + P_9 P^p_{11}\left(P^c_{12} - 1\right) - P^c_{12}\left(P_{10} + P_9\right)\right)} \\
&= \frac{\left(P_8\left(t_4 + t^m_8\right) + P_7 \begin{pmatrix} \left(1 - P_{10} - P_9\right)\left(t_4 + t_5 + t^m_8\right) - P_{10}\left(p^c_{12} - 1\right) \\ \left(t_4 + t_5 + t^c_7 + t^m_8\right) + \left(P^p_{11} - 1\right)\left(P^c_{12} - 1\right) P_9 \cdot \\ \left(t_4 + t_5 + t^p_6 + t^c_7 + t^m_8\right) \end{pmatrix} \right)}{P_8 + P_7\left(1 + P_9 P^p_{11}\left(P^c_{12} - 1\right) - P^c_{12}\left(P_{10} + P_9\right)\right)} \\
&= t_4 + t_5 + t^p_6 + t^c_7 + t^m_8 - \frac{\left(t_5 + t^p_6 + t^c_7\right) P_8 + P_7 \begin{pmatrix} (1 - P_9)(t^p_6 + t^c_7) \\ -P_{10}\left(t^c_7 + P^c_{12} t^p_6\right) \end{pmatrix}}{P_8 + P_7\left(1 + P_9 P^p_{11}\left(P^c_{12} - 1\right) - P^c_{12}\left(P_{10} + P_9\right)\right)}
\end{aligned} \tag{5.34}
$$

If the weight of material m from component c is g^c_m, the returned weight of m is

$$
M^{p,c}_m = P_{E_{07}} q_p q^p_c P_{E_{7,14}} g^c_m \cdot q_w = K^{p,c}_m \cdot q_w \tag{5.35}
$$

Where

$$K_m^{p,c} = \frac{P_3}{(1-P_2)} \cdot \left((1-P_4) + \frac{P_4 P_6}{(1-P_5)} \right)$$
$$\left(\left(P_8 + P_7 \left(1 - (P_9 + P_{10}) P_{12}^c - P_9 P_{11}^p (1 - P_{12}^c) \right) \right) P_{13}^m \right) q_p \cdot q_c^p \cdot g_m^c \quad (5.36)$$

And the total weight of the returned material is

$$\sum_m \sum_c \sum_p M_m^{p,c} = (\sum_m \sum_c \sum_p K_m^{p,c}) \cdot q_w = K_{material}^* \cdot q_w \quad (5.37)$$

where $K_{material}^*$ is the total renewable material in each product.

5.3.11 Forecasting discarded materials

Finally, from node 7 to node 15, which is the material to be discarded, the equivalence transfer function is

$$\begin{aligned} W_{E_{7,15}}^{p,c,m}(s) &= (w_{7,11} + w_{78}(w_{8,11} + (w_{8,10} + w_{89} w_{9,10}^p) w_{10,11}^c)) w_{11,15}^m + w_{7,15} \\ &= \mathrm{e}^{s(t_4 + t_8^m)} \left(P_8 + P_7 \mathrm{e}^{st_5} \begin{pmatrix} (1 - P_9 - P_{10}) \\ +(P_{10} + P_9 (1 - P_{11}^p) \mathrm{e}^{st_6^p})(1 - P_{12}^c) \mathrm{e}^{st_7^c} \end{pmatrix} \right) (1 - P_{13}^m) \\ &\quad + (1 - P_7 - P_8) e^{t_4 s} \end{aligned} \quad (5.38)$$

The probability and time of raw material manufacture for component c are

$$\begin{aligned} P_{E_{7,15}}^{p,c,m} &= (P_8 + P_7((1 - P_9 - P_{10}) + (P_{10} + P_9(1 - P_{11}^p))(1 - P_{12}^c)))(1 - P_{13}^m) \\ &\quad + (1 - P_7 - P_8) \\ &= (P_8 + P_7(1 - (P_9 + P_{10}) P_{12}^c - P_9 P_{11}^p (1 - P_{12}^c)))(1 - P_{13}^m) + (1 - P_7 - P_8) \end{aligned} \quad (5.39)$$

Lemma 3. The probability from node 7 to14 must be in the range of $[0, 1]$.

Proof.

$$\begin{aligned} &\text{Because} \quad 1 - P_9 - P_{10} \ge 0, 1 - P_7 - P_8 \ge 0, (1 - P_{11}^p) \ge 0, \\ &\qquad (1 - P_{12}^c) \ge 0, (1 - P_{13}^m) \ge 0; \ \text{ and } P_8, P_7, P_{10}, P_9, P_{13}^m \ge 0 \\ &\text{Therefore,} \quad P_{E_{7,15}}^{p,c,m} \ge 0 \end{aligned}$$

For $P_{E_{7,15}}^{p,c,m} = (P_8 + P_7(1-(P_9+P_{10})P_{12}^c - P_9 P_{11}^p(1-P_{12}^c)))(1-P_{13}^m)$
$+(1-P_7-P_8)$

Because, $0 \le (P_9 + P_{10}) \le 1$,

Hence, $P_{E_{7,15}}^{p,c,m} \le (P_8 + P_7(1-P_9 P_{11}^p(1-P_{12}^c)))(1-P_{13}^m) + (1-P_7-P_8)$;

also

because $P_9, P_{11}^p \ge 0$, and $(1-P_{12}^c) \ge 0$,

then $P_{E_{7,15}}^{p,c,m} \le (P_8+P_7)(1-P_{13}^m) + (1-P_7-P_8)$;

and because $0 \le P_7, P_8, (1-P_{13}^m) \le 1$, (5.40)

$(P_8+P_7)(1-P_{13}^m) + (1-P_7-P_8) = 1-(P_8+P_7)P_{13}^m$

Therefore, $P_{E_{7,15}}^{p,c,m} \le 1$

Hence, we have

$$\begin{aligned}\frac{\partial}{\partial s}W_{E_{7,15}}^{p,c,m}(s)\bigg|_{s=0} &= -\left(P_7+P_8-1\right)t_4 - \left(P_{13}^m-1\right)P_8\left(t_4+t_8^m\right)\\ &+\left(P_{13}^m-1\right)P_7\left(P_{10}+P_9-1\right)\left(t_4+t_5+t_8^m\right)\\ &+P_7P_{10}\left(P_{12}^c-1\right)\left(P_{13}^m-1\right)\left(t_4+t_5+t_7^c+t_8^m\right)\\ &-P_7P_9\left(P_{11}^p-1\right)\left(P_{12}^c-1\right)\left(P_{13}^m-1\right)\left(t_4+t_5+t_6^p+t_7^c+t_8^m\right)\end{aligned} \tag{5.41}$$

$$\begin{aligned}t_{E_{7,15}}^{p,c,m}(s) &= \frac{1}{P_{E_{7,15}}^{p,c,m}}\frac{\partial}{\partial s}[W_{E_{7,15}}^{p,c,m}(s)]\big|_{s=0}\\ &= \frac{\begin{pmatrix}-\left(P_7+P_8-1\right)t_4 - \left(P_{13}^m-1\right)P_8\left(t_4+t_8^m\right)\\ +\left(P_{13}^m-1\right)P_7\left(P_{10}+P_9-1\right)\left(t_4+t_5+t_8^m\right)\\ +P_7P_{10}\left(P_{12}^c-1\right)\left(P_{13}^m-1\right)\left(t_4+t_5+t_7^c+t_8^m\right)\\ -P_7P_9\left(P_{11}^p-1\right)\left(P_{12}^c-1\right)\left(P_{13}^m-1\right)\left(t_4+t_5+t_6^p+t_7^c+t_8^m\right)\end{pmatrix}}{\left((P_8+P_7(1-(P_9+P_{10})P_{12}^c-P_9P_{11}^p(1-P_{12}^c)))(1-P_{13}^m)+(1-P_7-P_8)\right)}\end{aligned} \tag{5.42}$$

If the weight of discarded material m from component j is d_m^c, the discarded weight of m is

$$D_m^{p,c} = P_{E_{07}} q_p q_c^p P_{E_{7,15}} d_m^c \cdot q_w = K_d^{p,c,m} \cdot q_w \tag{5.43}$$

Where

$$K_d^{p,c,m} = \frac{P_3}{(1-P_2)} \cdot \begin{pmatrix} (1-P_4)+ \\ \dfrac{P_4 P_6}{(1-P_5)} \end{pmatrix} \begin{pmatrix} \left(P_8 + P_7 \begin{pmatrix} 1-(P_9+P_{10})P_{12}^c \\ -P_9 P_{11}^p (1-P_{12}^c) \end{pmatrix} \right)(1-P_{13}^m) \\ +(1-P_7-P_8) \end{pmatrix} q_p \cdot q_c^p \cdot d_m^c \quad (5.44)$$

And the total weight of the returned component is

$$\sum_m \sum_c \sum_p D_m^{p,c} = (\sum_m \sum_c \sum_p K_d^{p,c,m}) \cdot q_w = K_{discard}^* \cdot q_w \quad (5.45)$$

where $K_{discard}^*$ is the total discarded material in each product.

5.4 Numerical example

A printer manufacturer begins to deal with product return and remanufacturing. Table 8 shows the probability and time duration of a printer return and recycling. One printer can be disassembled into four parts: ink cartridge, cleaning device, trolley and paper feeder. Each part contains screws, chips, plastic components and metal components (or some of them). In line with Figure 18, the parameters are listed in Tables 8-11.

Table 8. Probabilities and parameters in line with Figure 18.

P_1=0.95	P_2=0.3	P_3=0.6	P_4=0.8	P_5=0.15
P_6=0.7	P_7=0.2	t_0=0.6	$N_{(\mu_0=100, \sigma^2=30)}$	μ_1=60
t_1=0.1	t_2=0.1	t_3=0.1	t_4=0.15	q_w=1000

Table 9. Recycling probability and time for parts remanufacturing

	Remanufacture to parts P_8^p	Component dismantling	Processing time t_5^p	Quantity in each product q_p

	$1 - P_8^p$			
Ink cartridge (IC)	0.7	0.3	0.4	1
Cleaning device (CD)	0.3	0.7	0.5	1
Trolley (TO)	0.5	0.5	0.4	1
Paper feeder (PF)	0.8	0.2	0.3	1

Table 10. Recycling probability and time expectation for component remanufacturing

	Component remanufacturing P_9^c	Material recycling $(1 - P_9^c)$	Processing time t_6^c	Quantity in each part (IC, CD, TO, PF)q_c^p
Screw (SR)	0.95	0.05	0.1	(4, 4, 8, 4)
Chip (CI)	0.8	0.2	0.8	(0, 0, 1, 1)
Plastic component (PC)	0.6	0.4	0.3	(2, 1, 3, 1)
Metal component (MC)	0.7	0.3	0.4	(1, 2, 2, 1)

Table 11. Recycling probability and time for material recycling and disposal

	Material renewal P_{10}^{m}	Waste $1-P_{10}^{m}$	Processing time t_{7}^{m}	Weight in each part (SR, CI, PC, MC) $g_{m}^{c}(g)$
Plastic material	0.8	0.2	0.5	(0, 0.3, 0.5, 0)
Metal material	0.9	0.1	0.8	(0.1, 0.05, 0, 0.3)

(1) Prediction of product returns

Applying Equations (9)-(15) and Table 8, the probability of the product return is $P_{E_{07}} = 0.82$ and the expected return time is $t_{E_{07}} = 200.9$ weeks.

Although the mean μ and variance $\sigma^2 = \frac{\partial^2}{\partial s^2}[M_{E_{0n}}(s)]|_{s=0} - \mu^2$ can be derived, it is not possible to decide which distribution exactly is derivable. To verify the analytic result, we cross-checked it through a simulation in Matlab. The results of product return PDF is shown in Figure 20 and the cumulative probability function (CPF) in Figure 21. Figure 20 indicates that the expected product return peak time is week 200.94 with the probability of 82.04%, which matches the analytic result. In addition, the PDF shows a negative skewness. It means after the expected time, product return rate will rapidly reduce. This is useful information for remanufacturers when planning capacity in advance. From Figure 21, it suggests that the remanufacturer should consider allocating the major resources no later than week 150 when the return rate reaches 50%, for the sake of economic benefits.

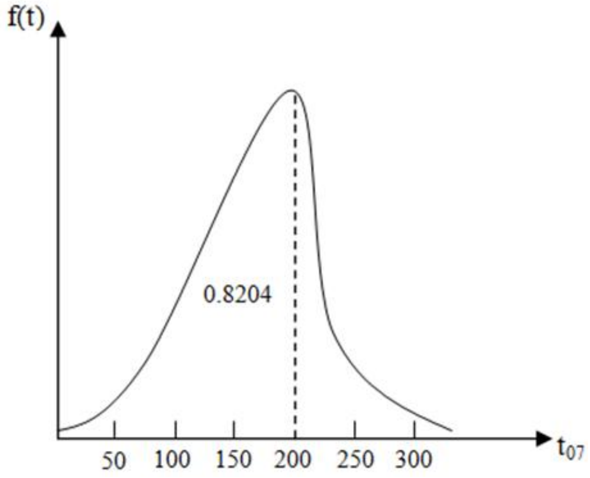


Figure 20. The simulation result of the product return's PDF showing the expected time 200.94 with the probability 0.8204

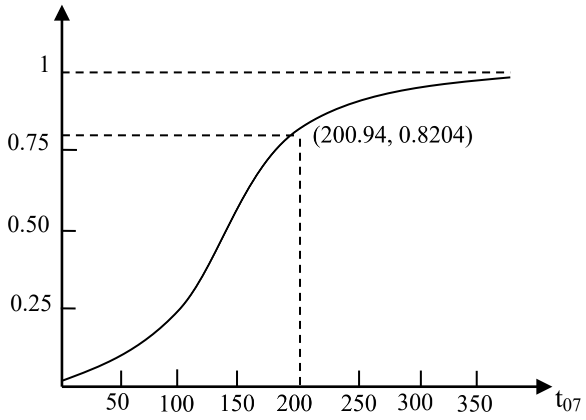


Figure 21. The simulation result of the product return's CPF

(2) Prediction of renewable parts

Applying Equations 5.16 and 5.22, the renewable parts probability and expected time are derived. For example, the probability and expected time for the ink cartridge are $P^{1}_{E_{7,12}} = 0.39$, $t^{1}_{E_{7,12}} = 0.65$ weeks.

(3) Prediction of remanufactured components

Remanufactured components can be predicted by using Equations 5.23-29. For example, the probability and expected time for the chip from the paper feeder are $P^{2,4}_{E_{7,13}} = 0.2176$, $t^{2,4}_{E_{7,13}} = 1.1735$ weeks.

(4) Prediction of extracted materials

For example, through Equations 5.30-37, the probability and expected time for remanufactured raw plastic from plastic parts on the trolley are $P_{E_{7,14}}^{3,3,1} = 0.32$, $t_{E_{7,14}}^{3,3,1} = 0.9350$ weeks.

(5) Prediction of disposal waste

Equations 5.38-45 are used to calculate the discarded waste. For example, the probability and expected time for discarded metal from metal parts on the cleaning device are $P_{E_{7,15}}^{2,4,2} = 0.09$, $t_{E_{7,15}}^{2,4,2} = 0.6341$ weeks.

For 1000 printers, the renewed, remanufactured, recycled and discarded materials are as follows:

(1) Through Equations 5.16-5.22, it suggests that 1054 parts will be remanufactured, including 321 ink cartridges, 137 cleaning devices, 229 trolleys and 367 paper feeders.

(2) There are 9664 remanufactured components, including 6335 screws, 467 chips, 1378 plastic components and 1484 metal components, by using Equations 5.23-29.

(3) Applying Equations 5.30-37, total recycled materials are 1827.4g, including 1180.1g plastic material and 647.3g metal material.

(4) Applying Equations 5.38-45, total discarded materials are 674.6g, including 491.9g plastic material and 182.7g metal material.

5.5 Summary

The model presented in this chapter aims to predict the quantity, probability and time of product returns, parts, and components remanufacturing, material extracting and final disposal. To achieve this, the GERT technique is applied to develop the forecasting model. The model can be used in any type of product and the remanufacturing process in general. The dynamics of a RL system is reflected by the model, which allows outputs which are desirable. The new approach and procedure introduced in the chapter can be adopted in any structure of PRR network. The output of which, combined with quantity, time and probability of return fulfils one of the research gaps identified in Chapter 2.

Chapter 6. The impact of products return on the system dynamic performance

6.1 Introduction

Product return has been analysed from a forecasting perspective in Chapter 5. Further to the discussion from the previous chapter, product take-back issues are analysed in this chapter from a system dynamics perspective, which addresses the research objective 4. The chapter aims to understand how product return impacts on system dynamic performance in a CLSC. Hence, it develops a SD model to simulate the CLSC system where RL activities are integrated with a forward SC. Figure 22 highlights chapter 6 in the structure of

the thesis.

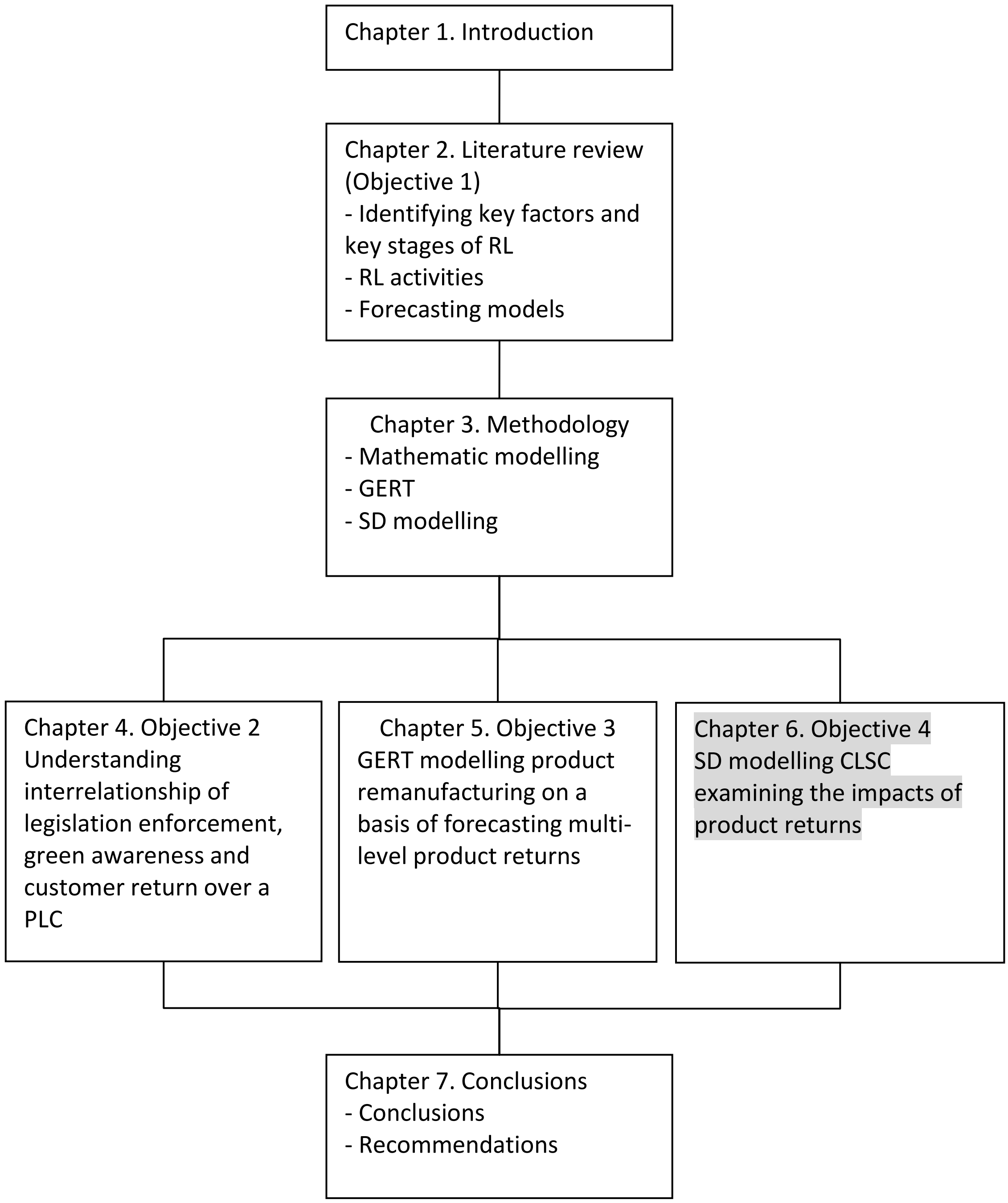


Figure 22. Research objective highlight of chapter 6

6.2 A systematic perspective of the CLSC

Economic performance has been well discussed in the majority of research in the area of CLSC, either from a minimizing total cost point of view or a maximizing profit point of view. Other performance measures are often neglected due to various research difficulties. In this chapter, the SD performance is taken as a measurement. The importance of taking SD performance into account are:

- It illustrates the interrelationship and interaction between stakeholders within a system;
- It provides a 'rich picture' of how a system responds to a sudden change, i.e. step response;
- It explains changing behaviour in a chaotic environment, such as random demand, lead-time uncertainties;
- It has implications of an economic consequence in terms of inventory holding, capacity utilisation and customer service failures.

The system we study here is shown as Figure 23. This is a manufacturer-centred CLSC consisting of a factory, a remanufacturing plant and RL operator. The manufacturer orders new materials from a supplier and/or recycled materials as well as remanufactured parts/components, in order to produce products to serve customers. Customers can return used product to a RL operator who sorts and classifies the returned product; for those salvageable returns, they will be put under the remanufacturing process. In this research, we assume remanufactured products are as good as new which will be stored in the serviceable inventory (SI) together with manufactured (new) products. Customer demand is satisfied from SI. This is rather common practice in industry, for instance, HP, Xerox, Estee Lauder, IBM, and many others (Kumar & Malegeant, 2006).

In analysing the CLSC, our focus lies on the behaviour of *serviceable inventory* and the *order rate* that the manufacturer places to the supplier. In SCM, these two elements are known to be directly relevant to customer satisfaction and operations cost. Because the higher serviceable inventory leads to higher customer satisfaction as the demand will always be met. Nevertheless, a higher inventory level results in higher cost such as storage cost, labour cost, warehousing operations cost, etc. Meanwhile, the order rate also reflects cost. The higher frequency at which an order is placed, the higher transport cost and ordering cost but lower storage cost. To minimise the total cost, when, where and how much to place an order is one of key decisions in operations.

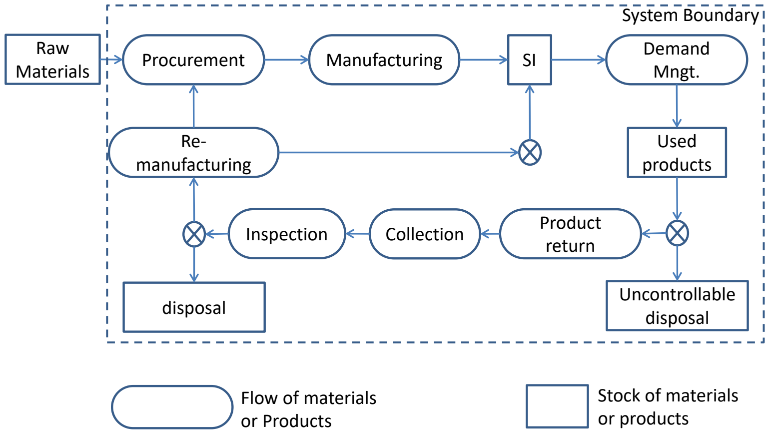


Figure 23. Structure of a manufacturer-centred CLSC

The SD approach needs to translate the system into a causal loop, i.e. the inputs and output of each process, the relationship of inputs and output, and the interaction between each of processes in the system. Figure 24 illustrates the causal loop of the CLSC system studied here. It is an extended variant version of Zhou and Disney (2006) and Tang and Naim (2004). The diagram starts from 'Customer Demand' in the middle right. After a certain period of use, the products are returned and will be collected either by a third party logistics or manufacturer in-house activity. The remanufacture-able quality will be judged in the process of inspection. The remanufactured product will be stored in the serviceable inventory with manufactured products to serve customer demand. The manufacturing decision is based on ordering policy which is affected by the facts of serviceable inventory level, work-in-progress (WIP), target inventory, and lead-times. There are four negative feedback loops which balance the system to find an equilibrium state. Loop B1 collection and inspection loop; Loop B2 manufacturing loop; Loop B3 WIP loop; and B4 is inventory feedback loop.

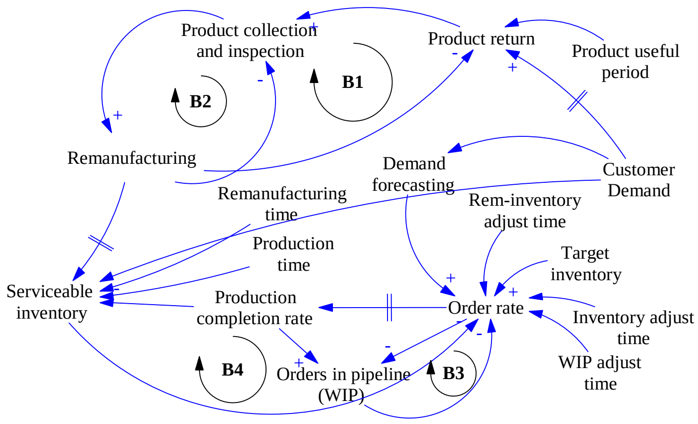


Figure 24. Causal loop diagram of the CLSC

The SD performance criteria are taken in this study as following: for a step response, peak overshoot (or undershoot) $\sigma\%$, peak time t_p , setting time t_s and rise time t_r (Zhou & Disney, 2006); for a random demand, bullwhip and inventory variance against demand (Zhou & Disney, 2006).

6.3 Model description

Figure 25 is the block diagram transferred from Figure24. It enables us to apply control theory to derive transfer functions.

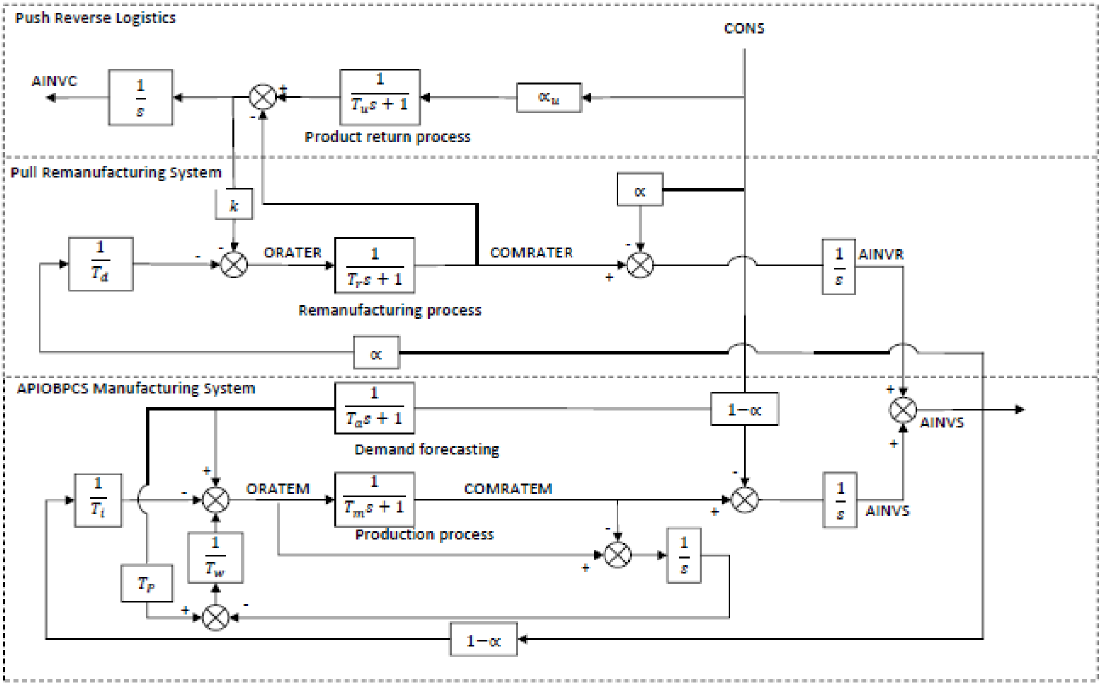


Figure 25. Block diagram of the CLSC

Assumptions:

All returned products can be used for remanufacturing.

Remanufactured product is as good as new.

The capacity for each of the activities is unlimited.

No stockout.

Notation:

CONS	Consumption or sales rate from customer
α_u	Return rate of used products
ORATER	Remanufacturer order rate
ORATEM	Manufacturer order rate placed on the pipeline
COMRATR	Remanufacturing completion rate
COMRATM	Production completion rate in the manufacturing pipeline
AINVR	Remanufacturing inventory
AINVM	Manufacturing inventory

AINVS	Actual serviceable stock, a sum of AINVR and AINVM
WIP	work-in-process in the pipeline
T_u	Useful time of a product till it returns to the system.
T_r	Actual remanufacturing pipeline lead-time
T_d	Time to adjust remanufacturing inventory
T_m	Actual manufacturing pipeline lead time
T_a	Time to average consumption, exponential smoothing parameter
T_i	Time to adjust manufacturing inventory
T_w	Time to adjust WIP
T_p	Estimated pipeline lead-time, a decision parameter that determines inventory-offset error
S	Laplace operator
k	Percentage of returned product into remanufacturing process, *a decision variable*
α	Percentage of total demand satisfied by remanufacturing, *a decision variable*

Note: Given that collection time and inspection time are much shorter than useful time, we assume T_u is the summary of the time that the product has been used by the customer, the product collection time and inspection time.

This model has three processes: RL including product return, collection and inspection; remanufacturing used products process; and manufacturing new products process.

RL process: a push system. Products return to the system after the useful period T_u. However, it is unlikely all of the used products will be returned. So, we assume the return rate is α_u. We assume that all of the returned products are remanufacturable. However, it is not necessary that all of the returned products be remanufactured for the sake of SD performance. So, the percentage of returned products entering the remanufacturing process is a decision variable, k , $k > 0$.

Remanufacturing process: a Kanban system (Zhou & Disney, 2006). It is a variant version of the APIOBPCS developed by (John et.al., 1994). This model has been widely adopted for the study of forward SC in many industries since then. Nevertheless, as it is suggested by Turrisi et al., (2013) that traditional APIOBPCS is not suitable in a RL process due to deteriorated performance. Rather, the system becomes more efficient only when APIOBPCS takes RL into consideration. The remanufacturing process is triggered by demand. The amount of remanufacturing depends on serviceable inventory level and demand.

Manufacturing process: an APIOBPCS system. It is an order-up-to inventory policy. The order rate is decided by three factors; demand forecasting, actual inventory level, and WIP.

$$ORATEM = Demand\ \ forecasting - actual\, service\, inventory - WIP$$

For each of the three factors, it also subject to the adjusted lead times, i.e. T_a demand smooth lead time; T_i inventory adjusted time; T_w WIP adjusted time. Note, the actual service inventory is the sum of remanufacturing inventory and manufacturing inventory.

6.4 Derivation of transfer functions

$$ORATEC = CONS\,\frac{\alpha_u}{\left(1+sT_u\right)} - \frac{ORATER}{1+sT_r} \qquad (6.1)$$

$$ORATER = AINVS\,\alpha(-\frac{1}{T_d}) - ORATEC \qquad (6.2)$$

Substitute Eq. (6.1) into Eq.(6.2) we have

$$ORATER = \frac{\left(1+sT_r\right)\left(\alpha_u CONS\,kT_d + \alpha AINVS\left(1+sT_u\right)\right)}{T_d\left(-1+k-sT_r\right)\left(1+sT_u\right)} \qquad (6.3)$$

$$COMRATER = \frac{ORATER}{1+sT_r} = \frac{\alpha_u CONS\, kT_d + \alpha AINVS\left(1+sT_u\right)}{T_d\left(-1+k-sT_r\right)\left(1+sT_u\right)} \tag{6.4}$$

$$AINVR = \frac{COMRATER}{\alpha CONS} \tag{6.5}$$

Substitute Eq (6.4) into Eq.(6.5)

$$AINVR = \frac{\begin{array}{l} -\alpha AINVS - \alpha CONST_d + \alpha CONS\, k\, T_d - \\ \alpha_u CONS\, k\, T_d - \alpha CONS\, s\, T_d T_r - \alpha AINVS\, sT_u - \\ \alpha CONS\, sT_d T_u + \alpha CONS\, k\, sT_d T_u - \alpha CONS\, s^2 T_d T_r T_u \end{array}}{sTd\left(1-k+sTrr\right)\left(1+sTu\right)} \tag{6.6}$$

$$COMRATEM = \frac{ORATEM}{1+sT_m} \tag{6.7}$$

$$WIP = \frac{(ORATEM - COMRATEM)}{s} = \frac{ORATEM\ T_m}{1+sT_m} \tag{6.8}$$

$$AINVM = \frac{ORATEM - (1-\alpha)CONS}{s} = \frac{(-1+\alpha)CONS + ORATEM}{s} \tag{6.9}$$

$$\begin{array}{l} AINVS = AINVR + AINVM = \\ \dfrac{\left(-1+\alpha\right)CONS + ORATEM}{s} + \\ \dfrac{\begin{array}{l} -\alpha AINVS - \alpha CONS\, T_d + \alpha CONS\, kT_d - \alpha_u CONS\, k\, T_d - \\ \alpha CONS\, sT_d T_r - \alpha AINVS\, sT_u - \alpha CONS sT_d T_u + \\ \alpha CONS\, ksT_d T_u - \alpha CONS\, s^2 T_d T_r T_u \end{array}}{sT_d\left(1-k+sT_r\right)\left(1+sT_u\right)} \end{array} \tag{6.10}$$

Solve Eq.(6.10) we obtain:

$$\frac{AINVS}{CONS} = \frac{T_d T_i \left(\begin{array}{l} \left(1-\alpha\right)\left(1+sT_a\right)T_p\left(1-k+sT_r\right)\left(1+sT_u\right) + \\ T_w\left(\begin{array}{l} \alpha_u k\left(1+sT_a\right) - \alpha\left(-1+k-sT_r\right)\left(1+sT_u\right) + \\ sT_a\left(1-k+sT_r\right)\left(1+sT_u\right) \end{array}\right) + \\ \left(1+sT_a\right)T_m\left(k\left(-1+\alpha_u - sT_u\right) + \left(1+sT_r\right)\left(1+sT_u\right)\right)\left(1+sT_w\right) \end{array}\right)}{\left(1+sT_a\right)\left(1+sT_u\right)\left(\begin{array}{l} aT_i T_m + a\left(T_i + sT_i T_m + T_d\left(-1+k-sT_r\right)\right)T_w + \\ T_d\left(1-k+sT_r\right)\left(T_w + sT_i\left(T_m + T_w + sT_m T_w\right)\right) \end{array}\right)} \tag{6.11}$$

Substitute Eq.(6.11) into

$$ORATEM = \frac{CONS(1-\alpha)}{(1+sT_a)} - \frac{AINVS(1-\alpha)}{T_i} + \frac{CONS(1-\alpha)T_p - WIP}{T_w} \qquad (6.12)$$

We obtain

$$\frac{ORATEM}{CONS} = \frac{(1-\alpha)(1+sT_m)\begin{pmatrix} s(1+sT_a)T_dT_iT_p(1-k+sT_r)(1+sT_u)+ \\ T_dT_w\begin{pmatrix}(1+s(T_a+T_i))(1+sT_r)(1+sT_u)+ \\ k(\alpha_u+\alpha_u sT_a-(1+s(T_a+T_i))(1+sT_u))\end{pmatrix}+ \\ \alpha T_i(1+sT_u)(T_p+sT_aT_p+T_w)\end{pmatrix}}{(1+sT_a)(1+sT_u)\begin{pmatrix} aT_iT_m + a(T_i+sT_iT_m+T_d(-1+k-sT_r))T_w + \\ T_d(1-k+sT_r)(T_w+sT_i(T_m+T_w+sT_mT_w))\end{pmatrix}}$$

(6.13)

Substitute Eq.(6.11) and Eq.(6.13) into Eq.(6.2), we have:

$$\frac{ORATER}{CONS} = \frac{(1+sT_r)\begin{pmatrix} \alpha^2T_i(1+sT_u)(T_p+sT_aT_p+T_w)- \\ \alpha_u k(1+sT_a)T_d(T_w+sT_i(T_m+T_w+sT_mT_w))+ \\ \alpha\begin{pmatrix}+\alpha_u k(1+sT_a)T_dT_w+ \\ T_i(1+sT_u)((1+sT_a)(T_m-T_p)+s(T_a+T_m+sT_aT_m)T_w)\end{pmatrix}\end{pmatrix}}{(1+sT_a)(1+sT_u)\begin{pmatrix} aT_iT_m + a(T_i+sT_iT_m+T_d(-1+k-sT_r))T_w + \\ T_d(1-k+sT_r)(T_w+sT_i(T_m+T_w+sT_mT_w))\end{pmatrix}}$$

(6.14)

6.5 Analysis of dynamic performance

This work focuses on two key outcomes: serviceable inventory level, and order rates for manufacturing and remanufacturing respectively. The corresponding transfer functions are derived in the previous section:

$$\frac{ORATER}{CONS}=\frac{\left(1+sT_r\right)\left(\begin{array}{l}\alpha^2T_i\left(1+sT_u\right)\left(T_p+sT_aT_p+T_w\right)-\\ \alpha_uk\left(1+sT_a\right)T_d\left(T_w+sT_i\left(T_m+T_w+sT_mT_w\right)\right)+\\ \alpha\left(\begin{array}{l}+\alpha_uk\left(1+sT_a\right)T_dT_w+\\ T_i\left(1+sT_u\right)\left(\left(1+sT_a\right)\left(T_m-T_p\right)+s\left(T_a+T_m+sT_aT_m\right)T_w\right)\end{array}\right)\end{array}\right)}{\left(1+sT_a\right)\left(1+sT_u\right)\left(\begin{array}{l}aT_iT_m+a\left(T_i+sT_iT_m+T_d\left(-1+k-sT_r\right)\right)T_w+\\ T_d\left(1-k+sT_r\right)\left(T_w+sT_i\left(T_m+T_w+sT_mT_w\right)\right)\end{array}\right)}$$

(6.15)

$$\frac{ORATEM}{CONS}=\frac{\left(1-\alpha\right)\left(1+sT_m\right)\left(\begin{array}{l}s\left(1+sT_a\right)T_dT_iT_p\left(1-k+sT_r\right)\left(1+sT_u\right)+\\ T_dT_w\left(\begin{array}{l}\left(1+s\left(T_a+T_i\right)\right)\left(1+sT_r\right)\left(1+sT_u\right)+\\ k\left(\alpha_u+\alpha_usT_a-\left(1+s\left(T_a+T_i\right)\right)\left(1+sT_u\right)\right)\end{array}\right)+\\ \alpha T_i\left(1+sT_u\right)\left(T_p+sT_aT_p+T_w\right)\end{array}\right)}{\left(1+sT_a\right)\left(1+sT_u\right)\left(\begin{array}{l}aT_iT_m+a\left(T_i+sT_iT_m+T_d\left(-1+k-sT_r\right)\right)T_w+\\ T_d\left(1-k+sT_r\right)\left(T_w+sT_i\left(T_m+T_w+sT_mT_w\right)\right)\end{array}\right)}$$

(6.16)

$$\frac{AINVS}{CONS}=\frac{T_dT_i\left(\begin{array}{l}\left(1-\alpha\right)\left(1+sT_a\right)T_p\left(1-k+sT_r\right)\left(1+sT_u\right)+\\ T_w\left(\begin{array}{l}\alpha_uk\left(1+sT_a\right)-\alpha\left(-1+k-sT_r\right)\left(1+sT_u\right)+\\ sT_a\left(1-k+sT_r\right)\left(1+sT_u\right)\end{array}\right)+\\ \left(1+sT_a\right)T_m\left(k\left(-1+\alpha_u-sT_u\right)+\left(1+sT_r\right)\left(1+sT_u\right)\right)\left(1+sT_w\right)\end{array}\right)}{\left(1+sT_a\right)\left(1+sT_u\right)\left(\begin{array}{l}aT_iT_m+a\left(T_i+sT_iT_m+T_d\left(-1+k-sT_r\right)\right)T_w+\\ T_d\left(1-k+sT_r\right)\left(T_w+sT_i\left(T_m+T_w+sT_mT_w\right)\right)\end{array}\right)} \quad (6.17)$$

The initial and final values for ORATER, ORATEM and AINVS (Nise 1994) as shown in Table 6.1.

Initial value: $\left.\frac{ORATER}{CONS}\right|_{s\to\infty}$, $\left.\frac{ORATEM}{CONS}\right|_{s\to\infty}$ and $\left.\frac{AINVS}{CONS}\right|_{s\to\infty}$

Final value: $\left.\frac{ORATER}{CONS}\right|_{s=0}$, $\left.\frac{ORATEM}{CONS}\right|_{s=0}$ and $\left.\frac{AINVS}{CONS}\right|_{s=0}$

Table 12. Initial and final values of the system receiving a unit step input

Measures	Initial	Final value
ORATER	0	$\dfrac{\alpha T_i\left(T_m+(\alpha-1)T_p\right)+\left((\alpha-1)\alpha_u k T_d+\alpha^2 T_i\right)T_w}{\alpha T_i T_m+\left((\alpha-1)(k-1)T_d+\alpha T_i\right)T_w}$
ORATEM	0	$\dfrac{(1-\alpha)\left(\left(1+(\alpha_u-1)k\right)T_d T_w+\alpha T_i\left(T_p+T_w\right)\right)}{\alpha T_i T_m+\left((\alpha-1)(k-1)T_d+\alpha T_i\right)T_w}$
AINVS	0	$-\dfrac{T_d T_i\left(\left(1+(-1+\alpha_u)k\right)T_m+(-1+\alpha+k-\alpha k)T_p+(\alpha-\alpha k+\alpha_u k)T_w\right)}{\alpha T_i T_m+\left((\alpha-1)(k-1)T_d+\alpha T_i\right)T_w}$

Observing Table 12, it can be noticed that $T_a, T_r, \text{and } T_u$ have no influence on the final values. But they will have an impact on other dynamics measures which will be analysed later.

There is a chance to adjust T_p to eliminate inventory off-set, that is AINVS' final value to be zero.

$$T_p=\frac{\left(1+(\alpha_u-1)k\right)T_m+(\alpha-\alpha k+\alpha_u k)T_w}{(1-\alpha)(1-k)} \tag{6.18}$$

The system has 11 parameters. In order to simplify the analysis, we start with the setting from (Zhou & Disney, 2006) which has been proved to be robust. $T_r=8$, $T_m=8$, $T_d=8$, $T_i=8$, $T_w=8$, $T_p=8$, $T_a=16$, and we assume $T_u=32$.

Product return rates vary according to the type of business and industry as shown in Table 13. However, as the CLSC studied is a linear system, the input of α_u does not affect the SD but only the magnitude. Without loss of generality, we set $\alpha_u = 0.3$.

Table 13. Examples of return rates by sector adapted from (Rogers & Tibben-Lembke, 2001)

Industry	Percentage
Publishing (Magazines)	50%
Publishing (Books)	20-30%
Distribution (Books)	10-20%
Manufacturing (Computers)	20-30%
Printers	18-35%
Auto Industry (Parts)	10-20%
Consumer electronics	18-25%
Household chemicals	4-8%

6.5.1 Dynamic performance with a step input

Sudden demand change is a very common phenomenon in the commercial world, for instance, a new outlet opening, a new product on the market, peak travelling time, festivals, etc. A step response can well reflect how the system copes with such a sudden change. It is powerful with two 'timeframes', i.e. transient period and steady state. The former refers to the 'copability' as well as 'capability' (Zhou et al. 2010), while the latter is a desired output. Analysing step response, the magnitude of overshoot implies the bullwhip effect and undershoot indicates the risk of stockout.

6.5.1.1 Test of extreme case

To grasp a quick understanding of the system's behaviour, we start from the extreme settings. The results are shown in Figure 26.

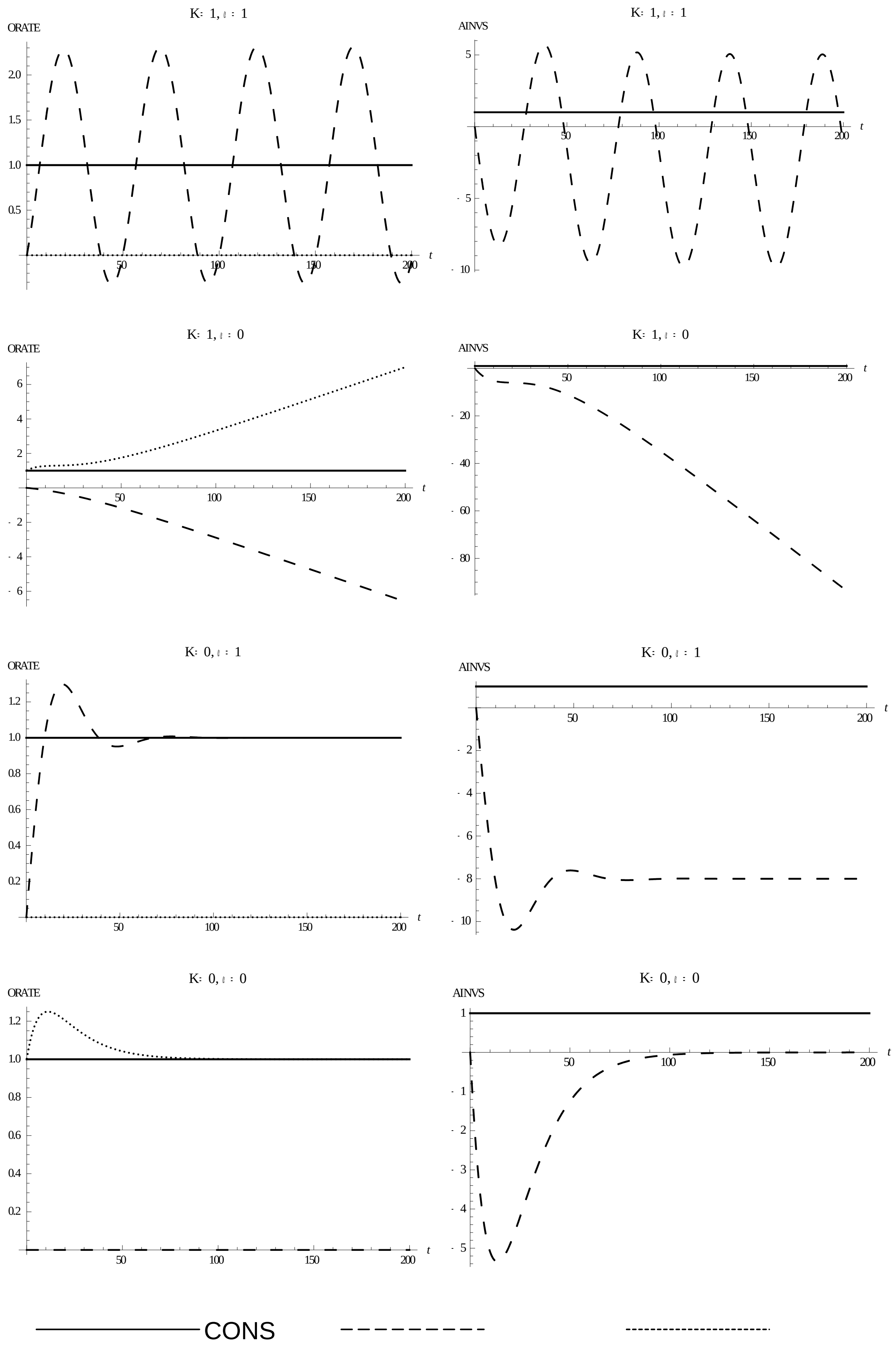


Figure 26. Test of extreme cases

Figure 26 indicates that:

- when $k = 1$, all of the returns go into the remanufacturing process. The result suggests that neither a remanufacturing system nor a manufacturing system can handle a large amount of returns individually. The remanufacturing system experiences constant oscillation and can never reach to a steady state, while the manufacturing system becomes unstable;
- when $k = 0$, $\alpha = 0$, it turns the hybrid system into a pure Kanban system. It can meet customer demand but at a cost of inventory off-set, longer rise time and settle time;
- when $k = 0, \alpha = 1$, it is a traditional APIOBPCS system. It copes with the sudden change very well and ends up with perfectly met customer demand and no inventory off-set.

Given $k > 0$ must hold, analysis of Figure 26 suggests that there might be opportunity to achieve a desired performance if we can coordinate production between manufacturing and remanufacturing, i.e. decision variable α , and decide a correct value of k .

6.5.1.2 Searching for the 'correct' decision variables k *and* α

This is a five order system with 11 parameters. So, it is not possible to derive an analytic form of optimisation. We therefore use Mathlab/Simulink control tools and a linear analysis tool to search for a good combination of k and α . The Simulink diagram is as shown in Figure 27.

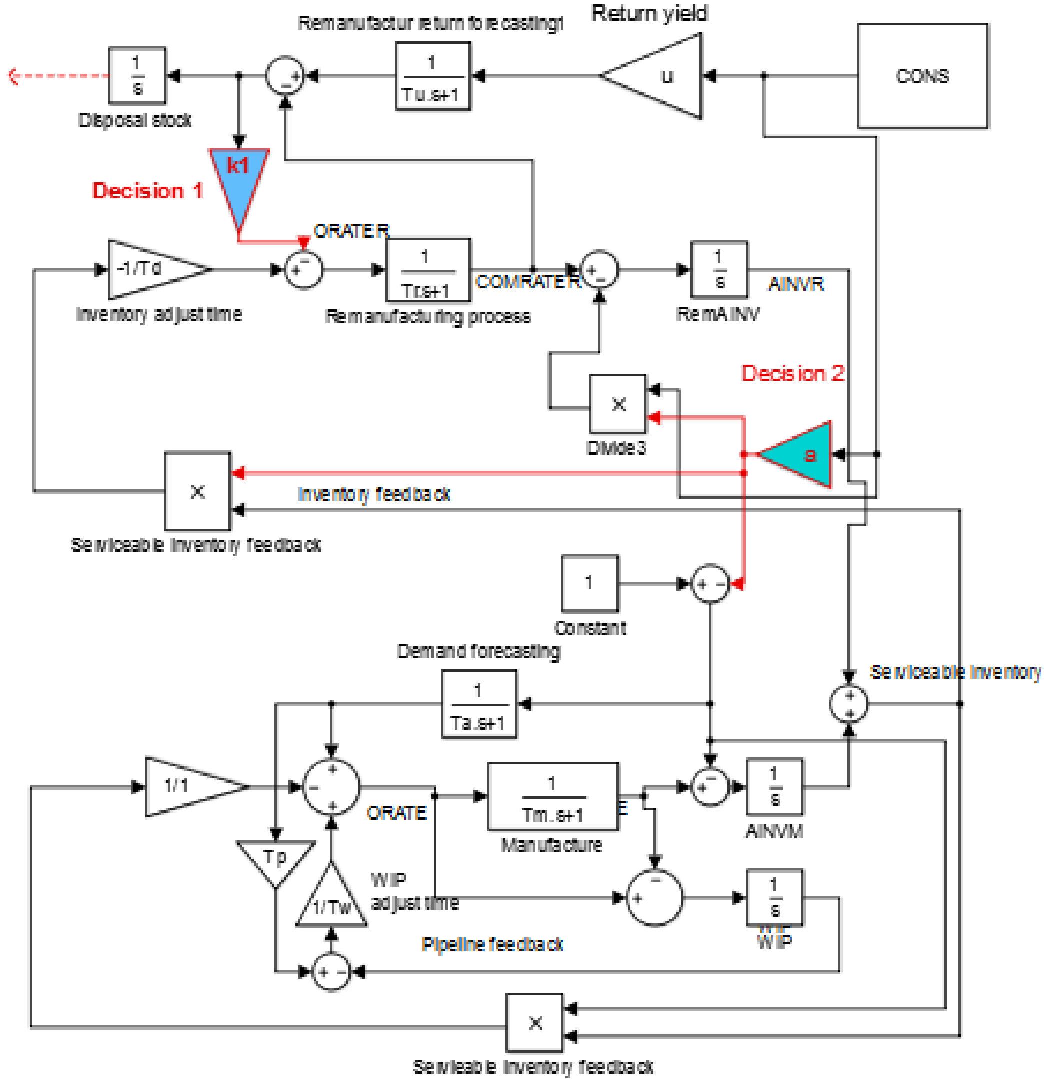


Figure 27. SimuLink simulation diagram

The criteria for good decisions are: (a) short rise time, t_r ; (b) short settling time, t_s ; (c) low overshoot in total ORATE, i.e. a sum of ORATER and ORATEM, P ; (d) small absolute undershoot in serviceable inventory, P .

- The rise time is when the first response time reaches to 90% of the final value. It indicates how quickly the system responds to a change;
- The settling time is the time that the system takes to reach 98% of the steady state of the final value, in other words, the time it takes to reach within a 2% error of the final value;

- Overshoot is the positive peak value of step response. It implies the magnitude of bullwhip. The lower the better;
- Undershoot is the negative peak value of inventory. It is an indication of stock-out risk. The bigger the better because it is a negative value.

As there are two sets of measurements for ORATE and serviceable inventory respectively, in order to assess the dynamics performance, we assign weight to each criterion: ORATE overshoot 60%; Serviceable inventory undershoot 60%; rising time 20%; and settle time 20%. The reasons for this allocation are that the peak value is always at a time of rising cost and rising settle time. A higher peak value usually results in a shorter rising time and a shorter settle time; while a desirable low peak value often leads to a slow rising time and a slow settle time. So, in control theory, the peak time is an important factor to be assessed.

Table 14. Step response performance criteria

k	α	AINVS				ORATE				Total ABS P
		P	t_p	t_r	t_s	P	t_p	t_r	t_s	
0.3	0.3	-9.06	18.10	2.64	98.4	1.28	18.5	5.83	62.28	10.34
	0.6	-9.96	20.00	5.83	83.52	1.22	19.49	6.99	49.84	11.18
	0.9	-10.97	22.16	8.90	54.76	1.17	20.5	8.31	42.76	12.14
0.6	0.3	-9.13	18.33	2.30	109.48	1.26	18.74	5.89	70.42	10.39
	0.6	-10.34	21.64	6.25	100.18	1.17	20.34	7.45	60.43	11.51
	0.9	-11.88	26.79	10.96	79.18	1.10	23.15	9.65	49.94	12.98
0.9	0.3	-9.20	18.74	2.03	116.01	1.25	19.12	5.95	75.81	10.45
	0.6	-10.70	23.60	6.63	110.69	1.14	22.08	7.95	68.81	11.84
	0.9	-12.92	33.20	13.24	91.288	1.04	29.34	11.54	57.15	13.96

Observing the above result, it suggests:

- For the serviceable inventory - AINVS

The higher the return percentage, the worse AINVS performance in terms of a bigger undershoot which indicates a higher risk of stock-out;

The higher the take-back percentage, the shorter the rising time but the longer the settling time to reach a steady state;

With the same value of take-back, the more production allocated to the remanufacturing process, the better the performance.

- For the order rate - ORATE

The ORATE performance is less sensitive to return rate, from a 30% to 60% increase, the overshoot changes 2%; from 60% to 90%, the overshoot changes 1%; This indicates the bullwhip phenomena may be insignificant in this system; both rise time and settling time are not sensitive to the return rate either.

Overall performance is calculated by the sum of the absolute value of two peaks, the lower the better. The result suggests, in general, taking a large amount of used products back into the system does not help to improve the SD performance as other papers suggested (Zhou & Disney, 2006). However, as sometimes manufacturers taking products back is not an option but a legislative obligation, the performance tends to be better if a remanufacturing process is used fully to meet customer demand. This is based on the assumption that customers have no preference between remanufactured products and virgin new products, which sometimes may not be the case.

6.5.2 Dynamic performance with random input

We are now going to study the impact of return rate and production allocation on dynamic performance when input is an independent and identically distributed (i.i.d) random. The dynamic performance is measured as Bullwhip and inventory variance amplification, which are defined as,

$$Bullwhip = \frac{\sigma^2_{ORATE}}{\sigma^2_{CONS}} \tag{6.19}$$

$$VarAINVS = \frac{\sigma^2_{AINVS}}{\sigma^2_{CONS}} \tag{6.20}$$

Both bullwhip and inventory variance amplification have been well studied in the last three decades. For better understanding of bullwhip and new developments within its research, we refer readers to the comprehensive literature review written by (Wang & Disney, 2015).

The inventory variance determines the stock levels required to meet a given target customer service level. The higher the variance of inventory levels, the more stock will be needed to maintain customer service at the target level (Churchman et al., 1957). Both the inventory variance and bullwhip directly affect the economics (Zhou & Disney, 2006). Thus, avoiding or reducing bullwhip and inventory variance has a very real and important impact on the performance of a supply chain.

The following results are obtained via Matlab/Simulink® over the 1000 time horizon.

Table 15. Bullwhip and Inventory Variance

k	α	Bullwhip	VarAINVS
0.3	0	0.1929	7.527
	0.3	0.1585	7.201
	0.6	0.1296	7.412
	0.9	0.1063	7.952
	1	0.0998	8.183
0.6	0	0.1973	7.647
	0.3	0.1561	7.243

	0.6	0.1210	7.502
	0.9	0.9222	8.273
	1	0.0840	8.624
0.9	0	0.2009	7.726
	0.3	0.1542	7.291
	0.6	0.1147	7.624
	0.9	0.0824	8.682
	1	0.0732	9.189
1.0	0	0.2019	7.747
	0.3	0.1537	7.307
	0.6	0.1129	7.668
	0.9	0.0797	8.828
	1	0.0701	9.393

Table 15 suggests that the well-known bullwhip effect doesn't exist in this CLSC, i.e. bullwhip<1. Interestingly and surprisingly, the more product returns, the less bullwhip exits. This might be because the returned products and remanufacturing process have been absorbing the chaos by feeding extra inventory to compensate for the shortage of the manufacturing process.

The allocation between manufacturing and remanufacturing suggests that it would be a good decision if remanufacturing has higher priority than manufacturing ($\alpha > 0.5$). This reflects the reality that a manufacturer-centred CLSC would always use returned product first to cut down cost. Only unsatisfied demand will be met from manufacturing process. However, this is based on a centralised decision-making mechanism, i.e. manufacturer can make a decision for both remanufacturing and manufacturing. For a decentralised decision-making environment, this result may not apply.

The result from inventory variance is different, which is not surprising. Because bullwhip and inventory variance always go hand-in-hand with conflict. That is, when bullwhip is relatively small, inventory variance is expected to be relatively big. So, if managing inventory is the main concern, the production allocation should be giving priority to manufacturing.

6.6 Summary

This chapter studies the impact of product return on the SD performance in a manufacturer-centred CLSC. The CLSC for analysis has three operations processes, i.e. collection, remanufacturing, and manufacturing.

The research outputs suggest, first, taking a large amount of products back to the system will cause a system to be unstable. So, a rational decision on how much to take-up is needed. Second, with a fixed product return rate, giving production priority to remanufacturing turns out to be a better choice than the other way around. Third, there is no bullwhip effect in this CLSC which is usually seen in a traditional SC.

The limitation of this research lies on: how we have rather simplified the case of this complex system by assuming unlimited capacities, which doesn’t reflect reality. In addition, the decision on the take-back is a static variable which should be a time-dependent variable. This leads to the same issue with production allocation which should be a k-dependent variable.

For future research, this model can be extended to a multiple-level and multiple products. In addition, a non-linear model which closely reflects reality could be studied in more detail.

CONCLUSION

Chapter 7. Conclusion

7.1 Summary of the research

As revealed in the previous chapters, the CLSC/RL research gaps mainly fall into the area of product returns. The thesis aims to overcome these gaps. To address this research aim, the thesis formulates its research objectives from both theoretical and practical levels.

At a theoretical level, the research has developed two new mathematical models to reflect (1) the relationship between legislative enforcement and consumers' product return decision, therefore, to understand how legislation and incentive schemes impact on product return behaviour; (2) the CLSC operational process, which includes remanufacturing process, integrated into manufacturing process. These two processes produce the finished goods to meet customer demand. The key decisions to be made in this CLSC system are ordering strategy and inventory level. The new CLSC model enables us to get a full picture of how return behaviour affects system dynamics, therefore, what is the right decision to enhance performance. In addition, the research advances GERT technique with Mason's rules in order to derive analytical results of product return forecasting. It makes big progress in return forecasting as it can predict different levels of returns, i.e. product, part, component and materials. Furthermore, apart from return quantity, the advanced GERT can also predict return timing.

At a practical level, these models, as closely as they could reflect reality, provide political and managerial insights. For authorities, the results from the first mathematical model indicate different levels of legislative enforcement resulting in different product return rate and different response/action from manufacturers. For practitioners, the return forecasting model offers in-advance information so resources can be allocated in the best way; the system dynamic model provides a full picture of how the return rate and ordering strategy impacts on system dynamics which is linked to the cost and customer satisfaction.

The conclusion chapter summarises (1) the research findings reflected against the research objectives, (2) how each of the achieved objectives contributes to either theory or methodology, and their indication to practices. Additionally, (3) research limitations and future research are discussed at the end.

7.2 Research findings

The thesis contributes to CLSC/RL research by focusing on overcoming the research gaps relating to products return. The following research objectives are designed to address the research aim.

O1 Identifying key factors and key phases within RL operations;

O2 Examining the impacts of legislative enforcement and green awareness towards product returns over a PLC;

O3 Developing an appropriate approach for product returns forecasting on a multi-level product return network;

O4 Exploring the impact of product returns on the system dynamic performance in the CLSC.

The research findings are reflected in relation to the research objectives.

O1: Key factors and key phases within RL operations

This objective is achieved through a comprehensive literature review. The key factors that drive and affect RL and CLSC operations are economic, environmental and social effects.

- Economic factors involve costs and profits generated within the process. While RL operation is often seen as a source of profit generation, it is also an extra cost for most companies. Unless the amount of returned products is up to a certain level, it is difficult for RL stakeholders (such as remanufacturers) to make any profit, which demotivates the involvement of SC stakeholders. The finding indicates the need for legislation and incentives to be in place in order to promote RL, and the cost reduction strategies must be developed for manufacturers and remanufactures. These strategies include a variety of value recovery options, depending on the type of product returned, its condition and its anticipated future demand.

- Environmental factors are often measured by the utilisation of nature resource and emissions, for instance, energy and CO2. This is, on one hand, enforced by legislation; on the other hand, demanded by customers. The manufacturers who produce low environmental impacting products gain green image which certainly promotes sales. However, it is evident that gaining green image comes with a price. So, there is a need for manufacturers to trade-off between economic benefits and environmental impact.

- Social factors are usually measured by job creation and wellbeing. However, as in this thesis we focus on RL and CLSC operations, the social factor is more towards the public awareness of green issues. Green issues increased profile in the public conscience gives rise to green awareness within businesses and manufacturers. A social change has begun to motivate manufacturers to allow these green issues to influence business decision making.

There are four phases in RL process: collection, sorting to decide: resale, repair, refurbish, remanufacturing phases including disassembly and recycling, and finally disposal. A map of a RL operation has been drawn. It provides an overview of how many activities are involved in a RL system; and RL alternatives have been identified. These alternatives offer the options for CLSC stakeholders to decide what the best for their business.

O2: Impacts of legislative enforcement and green awareness towards product returns over a PLC

Legislation plays a key role in a CLSC/RLSC. However, it is also difficult to assess quantitatively, and it is often excluded in quantitative analysis. Similarly, customer green awareness is often seen as a qualitative factor. In this research, the first model quantitatively interprets legislation and green awareness by measuring their strength. It provides a possible solution, which can be further applied in future research to draw a bigger picture including both quantitative and qualitative criteria.

The theoretical contribution can be assessed from the following aspects:

- It could be the first model that has been developed to quantify legislative enforcement, green awareness, and their relationship.
- The quantitative model has been presented to analyse the impacts. Customer return and customer demand are used to examine the impacts under different scenarios. Findings are:

- To customer return:

Customer return is affected by time, legislative enforcement and customer green awareness. Time can only affect customer return under the power of legislative enforcement and/or customer green awareness. The combined influence of legislative enforcement and customer green awareness determines the maximum accumulated customer returns of previously owned EOL products, which, hence, affects the initial customer return, at the latter return stage (i.e. Stage 2, see Chapter 4). The pattern of customer return when legislative enforcement increases follows a customer demand pattern. However, the impact of the same strength of legislative enforcement towards customer return becomes less and less when customer green awareness is strong enough to motivate customers to return their EOL products.

- To customer demand:

For this research, energy-efficient and non-energy-efficient products are used to compare and contrast customer demand under different legislative, awareness and price conditions. The increase of customer green awareness improves customer demand for energy-efficient products. Legislative enforcement improves customer demand for energy-efficient products through subsidy. The subsidy has time lag. Its inertia leads to a lesser influence on customer demand for energy-efficient products. Product price acts an important role as a determiner of customer demand. However, price differentiation has no influence when both/either customers and/or government act(s) as a stronger role than price in purchasing. Time acts as an inertia in customer purchasing behaviour.

The practical indications of the findings: (1) while the effect of legislative enforcement is appreciated, more efforts should be made to increase customer green awareness; (2) To promote energy efficient products, instead of legislation, an incentive/subsidy scheme would work better to encourage manufacturers to develop and produce energy efficient product, which is a win-win solution in the long term.

O3: Product return forecasting on a multi-level product return network

This research objective mainly contributes to methodology and practice.

The importance of forecasting is significant in remanufacturing operations. To construct a profitable remanufacturing process and RL system, its capacity planning, remanufacturing scheduling, inventory management, network design and resourcing allocation rely heavily on the amount of product return. These strategic plans are primarily based on return forecasting.

Nevertheless, due to the amount of uncertainties in RL, existing forecasting methods are not able to handle such complex structures that involving several rounds of feedback loops and uncertainties of return quantity, quality and timing. In order to capture the stochastic features of RL operations, the GERT method is seen as a good candidate (Pritsker and Happ, 1966; Samuel, 1956). However, the GERT is more simulation based technique with inherited limitations of simulation methodology. To be able to develop a generic return forecasting model, this research integrates Mason's rules to obtain analytic results of forecasting, which certainly contribute to the methodology in the area of product return forecasting.

The proposed model is able to predict products' return quantity, possibility of return and time through applying the theories of stochastic networks and control theory. Furthermore, it also can estimate time and the amount of detachable parts based on product structure; that is, BOM. The model would help EPR-responsible manufacturers and remanufacturers to improve the efficiency of production scheduling through forecasting.

O4: Impacts of product returns on the system dynamics in the CLSC

The theoretical contributions are: (1) the SD model itself has closely reflected the reality of CLSC operations. By taking both manufacturing and remanufacturing operations into consideration, the ordering strategy is developed to accommodate both operations; (2) the weighted optimisation is an innovative way of trading-off between different factors in a specific CLSC. (3) The finding suggesting that no bullwhip in the CLSC (which is usually seen in a traditional SC) provides the evidence of how RL could benefit both economically and environmentally simultaneously.

The indication of the findings to practice are explained following. Through studying the impact of product take-back on the SD performance in a manufacturer-centred CLSC. The result suggests:

- First, taking a large amount of products back to the system will cause the system to become unstable. So, a rational decision on how much to take-up is needed.
- Second, with a fixed return rate, giving production priority to remanufacturing turns out to be a better choice than the other way around.
- Third, no bullwhip effect in a well-designed CLSC would motivate more SC players to get involved in RL.

7.3 Limitations of research and future research opportunities

The limitations of the thesis lie in the general weaknesses of mathematical modelling as a research methodology, which include:

1. The research has to balance between complexity and mathematical achievability. In some cases, assumptions have to be made to simplify the model, which might be different from reality. However, the results from the model analyses do not lose the generality and are accountable for decision making.

2. The models which appear in the thesis may be mathematically challenging to general practitioners. There would be some difficulties when the models are applied in practical use. However, with the development of information technology and innovative software, I anticipate this could be a barrier easily overcome.

3. In addition, this research has been limited to authorities, customers, manufacturers and remanufacturers. Other stakeholders in a RL and CLSC have not been taken into account, for instance, finance institutions, product designers, etc. although I appreciate that these players are playing more and more important roles in RL.

For future research, (1) developing more complicated RL/CLSC models which take more stakeholders and their roles into consideration; (2) developing innovative analytic techniques to handle increasingly spanned data features and data volume, i.e. big data; (3) social impact in RL/CLSC appears to be an under-explored area. This is certainly an important yet challenging subject. (4) developing new business models resulting from cutting-edge technologies.

REFERENCES

Abernethy, M.A. and Brownell, P., 1999, The role of budgets in organizations facing strategic change: an exploratory study. Accounting, Organizations and Society, 24(3), 189–204.

Abraham, N., 2011, The apparel aftermarket in India – a case study focusing on reverse logistics. Journal of Fashion Marketing and Management: An International Journal, 15(2), 211–227.

Ahmed, E.A. Mohamed, 2013, Improving the Libyan customers' trust and acceptance for online. PhD thesis, University of Salford.

Ahmed, A., Kayis, B. and Amornsawadwatana, S., 2007, A review of techniques for risk management in projects. Benchmarking: An International Journal, 14(1), 22–36.

Albright, S., Winston, W.L., 2011. Management Science Modelling, 4th ed. South-Western College Publishing.

Alumur, S.A., Nickel, S., Saldanha-da-Gama, F. and Verter, V., 2012, Multi-period reverse logistics network design, European Journal of Operational Research, Vol. 220 No. 1, 67–78.

Amin, S.H. & Zhang, G., 2011, A proposed mathematical model for closed-loop network configuration based on product life cycle. The International Journal of Advanced Manufacturing Technology, 58(5-8), 791–801.

Amin, S.H. and Zhang, G., 2012, An integrated model for closed-loop supply chain configuration and supplier selection: Multi-objective approach. Expert Systems with Applications, 39(8), 6782–6791.

Aras, N. and Aksen, D., 2008, Locating collection centers for distance- and incentive-dependent returns. International Journal of Production Economics, 111(2), 316–333.

Asbjørnslett, B.E., 2008, Assessing the vulnerability of supply chains. In Supply Chain Risk: A Handbook of Assessment. New York: NY: Springer.

Avison, D.E. and Fitzgerald, G., 1995, Information system development:

methodologies, techniques and tools, McGraw-Hill.

Bayles, D.L., 2001, E-Commerce Logistics and fulfillment: delivering the goods, Prentice-Hall, Upper Saddle River, NJ.

Beamon, B.M., 1999, Designing the green supply chain. Logistics Information Management, 12(4), 332–342.

Bernon, M. and Cullen, J., 2007, An integrated approach to managing reverse logistics. International Journal of Logistics Research and Applications, 10(1), 41–56.

Biehl, M., Prater, E. and Realff, M.J., 2007, Assessing performance and uncertainty in developing carpet reverse logistics systems. Computers and Operations Research, 34(2), 443–463.

Bing, X., Bloemhof-Ruwaard, J.M. and van der Vorst, J.G.A.J., 2012, Sustainable reverse logistics network design for household plastic waste. Flexible Services and Manufacturing Journal, 26(1-2), 119–142.

Blanche, M.T., Durrheim, K. and Painter, D., 2007, Development studies and cross-disciplinarity- Research at the social science- physicalscience interface 2nd ed., Cape Town, South Africa: University of Cape Town Press.

Bo, B. and Yamamoto, K., 2010, Characteristics of E-waste Recycling Systems in. , 4(2), 429–435.

Brundland, G.H., 1998, European Union and Environment, Report, European Union, Luxemburg.

C.H.Hsieh, 2002, Grey neural network and its application to short term load forecasting problem. IEICE Trnnsactions an Information and Systems, E85-D(5), 897–902.

Cagno, E., Magalini, F. and Trucco, P., 2008, Modelling and planning of Product Recovery Network: the case study of end-of-life refrigerators in Italy. International Journal of Environmental Technology and Management, 8(4), 385.

Cairncross, F., 1992, How Europe's companies position to recycle, Harvard Business Review 70, 33-37.

Cannella, S., Bruccoleri, M. and Framinan, J.M., 2016, Closed-loop supply chains: What reverse logistics factors influence performance? International Journal of Production Economics, Forthcomin, 175, 35-49.

Carrasco-gallego, R. and Ponce-cueto, E., 2009, Forecasting the returns in reusable containers ' closed-loop supply chains . A case in the LPG industry . , 311–320.

Carter, C.R. and Ellram, L.M., 1998, Reverse logistics: A review of the literature and framework for future investigation, Journal of Business Logistics, 19(1), 85-102.

Chaabane, A., 2011, Design of sustainable supply chains under the emission trading scheme., PhD thesis.

Chouinard, M., D'Amours, S. and Aït-Kadi, D., 2008, A stochastic programming approach for designing supply loops. International Journal of Production Economics, 113(2), 657–677.

Christer, A.A.H. and Waller, W.M., 2015, Delay time models of industrial inspection maintenance problems. Journal of Operational Research Society, 35(5), 401–406.

Chuang, C.H., Wang, C.X. and Zhao, Y., 2014, Closed-loop supply chain Models for a High-tech product under alternative reverse channel and collection cost Structures. International Journal of Production Economics, 156, 108-123.

Chung, C.J. and Wee, H.M., 2008, Green-component life-cycle value on design and reverse manufacturing in semi-closed supply chain. International Journal of Production Economics, 113(2), 528–545.

Churchman, C.W., Ackoff, R.L. and Arnoff, E.L., 1957, Introduction to operations research, New York: John Wiley and Sons.

Clark, F.L., Deshier, D.D., Schumaker, J.B., Alley, G.R. and Warner, M.M., 1984,Visual imagery and self-questioning: strategies to improve comprehension of written material, Journal of Learning Disabilities, 17(3), 145–149.

Cruz-Rivera, R. and Ertel, J., 2009, Reverse logistics network design for the collection of End-of-Life Vehicles in Mexico. European Journal of Operational Research, 196(3), 930–939.

Cupchik, G.C., 2001, Constructivist realism: an ontology that encompasses positivist and constructivist approaches to the social sciences. Forum Qualitative Sozialforschung/Forum: Qualitative Social Research, 2(1), 1–8.

Dai, Z. and Zheng, X., 2015, Design of close-loop supply chain network under uncertainty using hybrid genetic algorithm: a fuzzy and chance-constrained programming model. Computers and Industrial Engineering, 88, 444–457.

Das, D. and Dutta, P., 2013, A system dynamics framework for integrated reverse supply chain with three way recovery and product exchange policy. Computers and Industrial Engineering, 66(4), 720–733.

Das, K. and Chowdhury, A.H., 2012, Designing a reverse logistics network for optimal collection, recovery and quality-based product-mix planning. International Journal of Production Economics, 135(1), 209–221.

Dean, J., 1950, Pricing Policies for New Products. Harvard Business Review, 28(6), 45-53.

Dekker, R., Fleischmann, M., Inderfurth, K., 2004, Reverse Logistics Quantitative Models for CLSC, Berlin Heidelberg, Germany: Springer-Verlag.

Demirel, N.Ö. and Gökçen, H., 2008, A mixed integer programming model for remanufacturing in reverse logistics environment. The International Journal of Advanced Manufacturing Technology, 39(11-12), 1197–1206.

Deng, J. 1982, Control problems of grey systems. Systems and Control Letters, 1(5), 288–294.

Denyer, D. and Tranfield, D., 2006, Using qualitative research synthesis to build an actionable knowledge base. Management Decision, 44(2), 213–227.

Diabat, A. and Simchi-levi, D., 2010, A Carbon-Capped Supply Chain Network Problem, 523-237.

Disney, S.M. and Towill, D.R., 2005, Eliminating drift in inventory and order based production control systems. International Journal of Production Economics, 93-94(1), 331–344.

Dowlatshahi, S., 2000, Developing a theory of reverse logistics. Interfaces, 30(3), 143-154.

Drumwright, M., 1994, Socially responsible organizational buying: environmental concern as a non-economic buying criterion. Journal of Marketing, 58(3), 1-19.

Du, F. and Evans, G.W., 2008, A bi-objective reverse logistics network analysis for post-sale service. Computers and Operations Research, 35(8), 2617–2634.

Du, L., Wu, J. and Hu, F., 2009, Logistics network design and optimization of closed-loop supply chain based on mixed integer nonlinear programming model. 2009 ISECS International Colloquium on Computing, Communication, Control and Management, 414–417.

Easterby-Smith, M.T. and Thorpe, R., 1991, Management research: An introduction, Sage Publication.

Edghill, J. and Towill, D.R., 1990, Assessing manufacturing system performance: frequency response revisited. Engineering Costs and Production Economics, 19, 319–326.

El-Sayed, M., Afia, N. and El-Kharbotly, A., 2010, A stochastic model for forward–reverse logistics network design under risk. Computers and Industrial Engineering, 58(3), 423–431.

Erol, İ., Nurtaniş Velioğlu, M., Sivrikaya Şerifoğlu, F., Büyüközkan, G., Aras, N., Demircan Çakar, N. and Korugan, A., 2010, Exploring reverse supply chain management practices in Turkey, Supply Chain Management: An

International Journal, 15(1), 43–54.

Fernandes, A.S., Gomes-Salema, M.I., and Barbosa-Povoa, A.P. (2010), The retrofit of a closed-loop distribution network: The case of lead batteries, Elsevier, 28,

Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J. and van Wassenhove, L. 2000, The impact of product recovery on logistics network design, Production and Operations Management, Vol. 10, 156–173.

Fleischmann, M. 2001, Quantitative Models for Reverse Logistics. Springer-Verlag, Berlin, Germany.

Fonseca, M.C., García-Sánchez, Á., Ortega-Mier, M. and Saldanha-da-Gama, F., 2009, A stochastic bi-objective location model for strategic reverse logistics. Top, 18(1), 158–184.

Forrester, J.W., 1961, Industrial dynamics, Cambridge, MA: MIT Press.

Francas, D. and Minner, S., 2009, Manufacturing network configuration in supply chains with product recovery. Omega, 37(4), 757–769.

Fu, N., Lao, H.C. and Varakantham, P., 2015, Robust execution strategies for project scheduling with unreliable resources and stochastic durations. Journal of Scheduling,18(6), 607-622.

Fukuyama, F., 1995, The economics of trust. National Review, 47, 42.

Gammelgaard, B., 2004, Schools in logistics research? a methodological framework for analysis of the discipline. International Journal of Physical Distribution and Logistics Management, 34(6), 479–491.

Gattorna, J., 1998, Strategic supply chain alignment - best practice in supply chain management, Gower Publishing, Aldershot.

Geyer, R. and Blass, V., 2009, The economics of cell phone reuse and recycling, The International Journal of Advanced Manufacturing Technology, 47(5-8), 515–525.

Glaser, B., 1992, Basics of grounded theory analysis, Mill Valley, CA: Sociology

Press.

Godfrey, R., 1998, Ethical purchasing: Developing the supply chain beyond environment, In: Russel, T. ed. Greener purchasing: Opportunities and innovations. Sheffield: Greenleaf Publishing, 244-251.

Golinska, P., Kosacka, M., Mierzwiak, R. and Werner-Lewandowska, K., 2014, Grey decision making as a tool for the classification of the sustainability level of remanufacturing companies, Journal of Cleaner Production, 105, 28–40.

González-Torre, P., Álvarez, M., Sarkis, J. and Adenso-Díaz, B., 2010, Barriers to the Implementation of Environmentally Oriented Reverse Logistics: Evidence from the Automotive Industry Sector. British Journal of Management, 21(4), 889–904.

Govindan, K., Soleimani, H. and Kannan, D., 2014, Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. European Journal of Operational Research, 240(3), 603–626.

Grant, D.B. and Banomyong, R., 2010, Design of closed-loop supply chain and product recovery management for fast-moving consumer goods. Asia Pacific Journal of Marketing and Logistics, 22(2), 232–246.

Guba, E.G. and Lincoln, Y.S., 1994, Competing paradigms in qualitative research. Handbook of qualitative research, 105–117.

Guide V.D.R. and Van Wassenhove L.N., 2009, The evolution of closed-loop supply chain research. Operation Research, 57(1), 10-18.

HA., S., 1952, On the application of servomechanism theory in the study of production control. Econometrica, 20, 247–68.

Halabi, A.X., Torres, J.R.M., Pirachicán, D.C. and Mejía, D., 2013, A modelling framework of reverse logistics practices in the Colombian plastic sector, International Journal of Industrial and Systems Engineering, 13(3), 364-387.

Han, X., Chen, D., Chen, D. and Long, H., 2015, Strategy of production and ordering in closed-loop supply chain under stochastic yields and stochastic demands, 8(4), 77–84.

Hanafi, J., Kara, S. and Kaebernick, H., 2008, Reverse logistics strategies for end-of-life products. The International Journal of Logistics Management, 19(3), 367–388.

Hazen, B.T., Hall, D.J, and Hanna, J.B., 2012, Reverse logistics disposition decision-making: developing a decision framework via content analysis, International Journal of Physical Distribution and Logistics Management, 42(3) , 244-274.

Hines, F., and Johns, R., 2001, Environmental supply chain management: Evaluating the use of environmental mentoring through supply chain, Greening of Industry Network Conference. Bangkok, January 21-25.

Homer, J.B. and Hirsch, G.B., 2006, System dynamics modeling for public health: background and opportunities, American Journal for Public Health, 96(3), 452-458.

Horneber, M., 1995, Innovatives entsorgungsmanagement: methoden und instrumente \ur vermeidung und bewältigund von umweltbelastungen, Vandenhoek & Ruprecht.

Hsueh, C. and Chang, M., 2008, Equilibrium and analysis and corporate social responsibility for supply chain integration, European Journal of Operational Research, 190(1), 116-129.

Hu, H., Hu, X., Meng, Z. and Zhai, W., 2015, Research on recycling strategy of retailer cooperating with the third-party in closed-loop supply chain, Etmhs, 941–945.

Huang, Y.P., 1983, A Q-GERT network simulation model for a voice-data communication system, Virginia Polytechnic Institute and State University Press.

Huang, Y., Huang, C. and Science, C., 1995, A genetic-based fuzzy grey prediction model. , 1051–1056.

Hung Lau, K. and Wang, Y., 2009, Reverse logistics in the electronic industry of

China: a case study. Supply Chain Management: An International Journal, 14(6), 447–465.

Jackson, M. C., 2001, Critical systems thinking and practice, European Journal of Operational Research, 128 (2), 233-244.

Jim Wu, Y. and Cheng, W., 2006, Reverse logistics in the publishing industry: China, Hong Kong, and Taiwan B. S. Sahay, ed. International Journal of Physical Distribution and Logistics Management, 36(7), 507–523.

John, S., Naim, M.M. and Towill, D.R., 1994, Dynamic analysis of a WIP-compensated decision support system. International Journal of Management Systems Design, 1(4), 283–297.

Kannan, D., Diabat, A., Alrefaei, M., Govindan, K. and Yong, G., 2012, A carbon footprint based reverse logistics network design model, Resources, Conservation and Recycling, Elsevier B.V., 67, 75–79.

Kara, S.S. and Onut, S., 2010, A two-stage stochastic and robust programming approach to strategic planning of a reverse supply network: The case of paper recycling. Expert Systems with Applications, 37(9), 6129–6137.

Kaya, O. and Urek, B., 2016, A mixed integer nonlinear programming model and heuristic solutions for location, inventory and pricing decisions in a closed loop supply chain. Computers and Operations Research, 65, 93–103.

Ke, J.C. and Wang, K.H., 1999, Cost analysis of the M/M/R machine repair problem with balking, reneging, and server breakdowns. Journal of the Operational Research Society, 50(3), 275–282.

Kiff, J.S., Chieux, T., Simmons, D., Scheffer, F. and Buzzavo, L., 1998. Major opportunities for cost savings and improved customer services: parts supply systems in the franchise after-market in France, Germany, Italy, UK. International Car Distribution Programme.

Ko, H.J. and Evans, G.W., 2007, A genetic algorithm-based heuristic for the dynamic integrated forward/reverse logistics network for 3PLs. Computers and Operations Research, 34(2), 346–366.

Kopicki, R., Berg, M., Legg, L., Dasappa, V., Maggioni, C., 1993, Reuse and Recycling – Reverse Logistics Opportunities, Council of Logistics Management, Oak Brook, Illinois

Kosugi, T., Hayashi, A., Matsumoto, T., Akimoto, K., Tokimatsu, K., Yoshida, H., Tomoda, T., 2004, Time to realization: Evaluation of CO2 capture technology RandDs by GERT (Graphical Evaluation and Review Technique) analyses, Energy, 29(9-10), 1297–1308.

Kovacs, G. and Spens, K.M., 2005, Abductive reasoning in logistics research. International Journal of Physical Distribution and Logistics Management, 35(2), 132–144.

Krikke, H., 2011, Impact of closed-loop network configurations on carbon footprints: A case study in copiers. Resources, Conservation and Recycling, 55(12), 1196–1205.

Krippendorff, K., 2012, Content analysis: An introduction to its methodology, London: Sage., 114.

Krumwiede, D.W. and Sheu, C., 2002, A model for reverse logistics entry by third-party providers. Omega, 30(5), 325–333.

Kucharavy, D. and De Guio, R., 2008, Application of S-shaped curves. Procedia Engineering, 9, 559–572.

Kuhnell, B.T., Luo, M. and Wang, R., 1991, Forecasting machin condition using Grey-system theory, In International Machinery Monitoring and Diagnostic Conference, 2nd, 102–105.

Kumar, S. and Malegeant, P., 2006, Strategic alliance in a closed-loop supply chain, a case of manufacturer and eco-non-profit organization. Technovation, 26(10), 1127–1135.

Kumar, S. and Putnam, V., 2008, Cradle to cradle: Reverse logistics strategies and opportunities across three industry sectors. International Journal of Production Economics, 115(2), 305–315.

Kumar, S. and Yamaoka, T., 2007, System dynamics study of the Japanese automotive industry closed loop supply chain. Journal of Manufacturing Technology Management, 18(2), 115–138.

Kurihara, K. and Nishiuchi, N., 2002, Effcient Monte Carlo simulation method of GERT-type network for project management. , 42, 521–531.

Kusumastuti, R.D., Piplani, R. and Hian Lim, G., 2008, Redesigning closed-loop service network at a computer manufacturer: A case study. International Journal of Production Economics, 111(2), 244–260.

Lau K. and Wang Y., 2009, Reverse logistics in the electronic industry of China: a case study, Supply Chain Management: An International Journal, 14(6), 447-465.

Lee, C.K.M. and Chan, T.M., 2009, Development of RFID-based reverse logistics system. Expert Systems with Applications, 36(5), 9299–9307.

Lee, D.H. and Dong, M., 2008, A heuristic approach to logistics network design for end-of-lease computer products recovery. Transportation Research Part E: Logistics and Transportation Review, 44(3), 455–474.

Lee, D.H., Dong, M. and Bian, W., 2010, The design of sustainable logistics network under uncertainty. International Journal of Production Economics, 128(1), 159–166.

Lee, J.E., Gen, M. and Rhee, K.G., 2009, Network model and optimization of reverse logistics by hybrid genetic algorithm. Computers and Industrial Engineering, 56(3), 951–964.

Lieb, R. and Randall, H., 1999, CEO perspectives on the current status and future prospects of the third party logistics industry in the United States, Transportation Journal, 38(3), 28-42.

Lin, K.P., Wu, M.J., Hung, K.C. and Kuo, Y., 2011, Developing a Tω (The Weakest T-Norm) fuzzy GERT for evaluating uncertain process reliability in semiconductor manufacturing, Applied Soft Computing, Elsevier B.V., 11(8), 5165–5180.

Lin, Y., 2004, A historical introduction to grey systems theory. 2004 IEEE International Conference on Systems, Man and Cybernetics (IEEE Cat. No.04CH37583), 3, 2403–2408.

Liu, S., Forrest, J. and Yang, Y., 2012, A brief introduction to grey systems theory. Grey Systems: Theory and Application, 2(2), 89–104.

Maslennikova I. and Foley D., 2000, Xerox's approach to sustainability, Interfaces, 30(3), 226-233.

Mason, S.J., 1956, Feedback theory-further properties flow graphs. Proceedings of the IRE, 44(7), 920–926.

Matsumoto, M. and Umeda, Y., 2011, An analysis of remanufacturing practices in Japan. Journal of Remanufacturing, 1(1), 283-295.

Memon, M.S., Lee, Y.H. and Mari, S. I., 2015, Group multi-criteria supplier selection using combined grey systems theory and uncertainty theory. Expert Systems with Applications, 42(21), 7951–7959.

Mitchell, M. A., LeMay, S. A., Arnold, D.R., and Turner, G.B., 1993, Symbiotic logistics, International Journal of Logistics Management, 3(2), 19-30.

Mochizuki, M., Wada, Y., Kaku, K., and Toshima, T., 2001, Use of recyclable packing materials, Yokogawa Technical Report English Edition, 31, 20-21.

Mohammed N Shaik, Walid Abdul-Kader, 2012, Performance measurement of reverse logistics enterprise: a comprehensive and integrated approach, Measuring Business Excellence, 16(2), 1-22.

Morita, H., Kase, T., Tamura, Y. and Iwamoto, S., 1996, Interval prediction of annual maximum demand using grey dynamic model, International Journal of Electrical Power and Energy Systems, 18(7), 409–413.

Mukherjee, K. and Mondal, S., 2009, Analysis of issues relating to remanufacturing technology – a case of an Indian company. Technology Analysis and Strategic Management, 21(5), 639–652.

Müller, A. and Thun, J., 2010, An empirical analysis of green supply chain management in the German automotive industry, Business Strategy and Environment, 132, 119–132.

Murphy, P., 1986, A preliminary study of transportation and warehousing aspects of reverse distribution, Transportation Journal, 25, 12-21.

Murphy, P.R., Poist, R.F., and Braunschweig, C.D., 1995, Role and relevance of logistics ot coporate environmentalism, International Journal of Physical Distribution and Logistics Management, 25(2), 5-19.

Nagurney, A. and Toyasaki, F., 2003, Supply chain supernetworks and environmental criteria. Transportation Research Part D: Transport and Environment, 8(3), pp.185–213.

Neto, J.Q.F., Walther, G. and Bloemhof, J., 2011, From closed-Loop to sustainable supply chains: The WEEE case.

Nevins, J. L. and Money, R. B., 2008, Performance implications of distributor effectiveness, trust, and culture in import channels of distribution. Industrial Marketing Management, 37(1), 46-58.

Nise, N.S., 1994, Control systems engineering, The Benjamin/Cummings Publishing Company, Inc, California.

Olugu, E.U. and Wong, K.Y., 2012, An expert fuzzy rule-based system for closed-loop supply chain performance assessment in the automotive industry. Expert Systems with Applications, 39(1), 375–384.

Pena-Mora, F. and Li, M., 2001, Dynamic planning and control methodology for design/build fast-track construction projects. Journal of Construction Engineering and Management, 1, 1–18.

Pishro-Nik, H., 2014, Introduction to probability, statistics, and random processes, Kappa Research, LLC. 324-329.

Pishro-Nik, H., 2016, Moment generating functions.

Pochampally, K.K. and Gupta, S.M., 2004, A business-mapping approach to multi-criteria group selection of collection centers and recovery facilities, IEEE International Symposium on Electronics and the Environment, 2004. Conference Record. 2004, IEEE, 249–254.

Pritsker, A.A.B. and Happ, W.W., 1966, GERT:Graphical evaluation and review technique, Part I, Fundamental. Journal of Industrial Engineering, 17(5), 267–74.

Quariguasi Frota Neto, J. and Van Wassenhove, L.N., 2013, Original equipment manufacturers' participation in take-Back initiatives in Brazil. Journal of Industrial Ecology, 17(2), 238–248.

Ravi, V., 2005, Analyzing alternatives in reverse logistics for end-of-life computers: ANP and balanced scorecard approach, Computers and Industrial Engineering, 48(2), 327-356.

Rogers, D.S. and Tibben-Lembke, R., 2001, An examination of reverse logistics practices. Journal of Business Logistics, 22(2), 129–148.

Saunders, M.N.K., Lewis, P. and Thornhill, A., 2009, Research Methods for Business Students 5th ed., Harlow: England: Pearson Education Limited.

Schofield, J., 1993, Increasing the generalizabiltiy of qualitative research. In Social research: Philosophy, Politics and Practice. London: Open University and Sage, 200–225.

Seitz, M. A., 2007, A critical assessment of motives for product recovery: the case of engine remanufacturing, Journal of Cleaner Production, 15(11-12), 1147–1157.

Seuring, S. and Müller, M., 2008, From a literature review to a conceptual framework for sustainable supply chain management. Journal of Cleaner Production, 16(15), 1699–1710.

Seuring, S., 2013, A review of modeling approaches for sustainable supply chain management, Decision Support System, 54(4), 1513-1520.

Shankar, G. and Mohapatra, B.N., 1993, GERT Analysis of Conditional Repetitive Group Sampling Plan. International Journal of Quality and Reliability Management, 10(2), 50-62.

Shankar, G. and Sahani, V., 1995, GERT analysis of a two-unit cold standby system with repair. Microelectronics Reliability, 35(5), 837–840.

Sherwood, D., 2002, Seeing the forest for the trees – a manager's guide to applying systems thinking. London: Nicholas Brealey Publishing.

Simon, H.A., 1952, On the application of servomechanism theory in the study of production control, Econometrica, 20(2), 247-268.

Spiegler, V.L.M, 2013, Designing supply chains resilient to nonlinear system dynamics, PhD thesis, Cardiff University.

Srivastava, S.K., Rajiv, K., 2006, Managing product returns for reverse logistics, International Journal of Physical Distribution & Logisitcs Management, 36(7), 524-546.

Sterman, J., 2000, Business Dynamics: Systems Thinking and Modelling for a Complex World, NY: McGraw-Hill.

Subramoniam, R., Huisingh, D. and Chinnam, R. B., 2010, Aftermarket remanufacturing strategic planning decision-making framework: theory and practice. Journal of Cleaner Production, 18(16-17), 1575–1586.

Sumner, A. and Tribe, M., 2008, Development studies and cross-disciplinarity: Research at the social science- physicalscience interface. Journal of International Development, 20(1), 751–767.

Sum, C.C., & Tao, C.B., 1999, Strategic posture of logistics providers in Singapore, International Journal of Physicla Distribution and Logistics Management, 29-9, 588-605.

Talbot, S., Lefebvre, É. and Lefebvre, L., 2007, Closed-loop supply chain activities and derived benefits in manufacturing SMEs. Journal of Manufacturing Technology Management, 18(6), 627–658.

Tang, H., 2015, A novel fuzzy soft set approach in decision making based on grey relational analysis and Dempster–Shafer theory of evidence. Applied Soft Computing, 31, 317–325.

Tang, O. and Naim, M. M., 2004, The impact of information transparency on the dynamic behaviour of a hybrid manufacturing/remanufacturing system. International Journal of Production Research, 42(9), 4135–4152.

Taylor, B.R. and Andrushchenko, I. V., 2014, Interaction of water temperature and shredders on leaf litter breakdown: A comparison of streams in Canada and Norway. Hydrobiologia, 721(1), 77–88.

Toro, M. and Aracil, J., 1988, Qualitative analysis of system dynamics ecological models, System Dynamics Review, 4(1-2), 56-80.

Thierry, M., Salomon, M., Van Nunen, J., Van Wassenhove, L., 1995, Strategic issues in product recovery management, California management review 37(2), 114-135.

Tibben-Lembke, R.S. and Rogers, D.S., 2002, Differences between forward and reverse logistics in a retail environment, Supply Chain Management: An International Journal, 7 (5), 271-282.

Toffel, M.W., 2003, The growing strategic importance of end-of-life product take-back, Interfaces, 45(3), 102-129.

Tonanont, A., Yimsiri, S., Jitpitaklert, W. and Rogers, K.J., 2008, Performance evaluation in reverse logistics with data envelopment analysis, Proceedings of the 2008 Industrial Engineering Research Conference, 764-770

Towill, D.R., Naim, M.M. and Wikner, J., 1992, Industrial dynamics simulation models in the design of supply chains. International Journal of Physical Distribution and Logistics Management, 22(5), 3–13.

Turrisi, M., Bruccoleri, M. and Cannella, S., 2013, Impact of reverse logistics on supply chain performance. International Journal of Physical Distribution and Logistics Management, 43(7), 564–585.

Vlachos, D., Georgiadis, P. and Iakovou, E., 2007, A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains, Computers & Operations Research, 34(2), 367–394.

Verstrepen, S., Cruijssen, F., Brito, M.P. De and Dullaert, W., 2007, An exploratory analysis of reverse logistics in flanders, European Journal of Transport and Infrastructure Research, 4(4), 301–316.

Virginia Luisa Marques Spiegler, 2013, Designing supply chains resilient to nonlinear system dynamics, Cardiff University, PhD thesis.

Wang, X. and Disney, S.M., 2015, The bullwhip effect: Progress, trends and directions, European Journal of Operational Research, 250(3), 691-701.

Wang, Y., 2002, Predicting stock price using fuzzy grey prediction system, Expert Systems with Applications, 22(1), 33–38.

Webster, J. and Watson, R.T., 2002, Analyzing the past to prepare for the future: writing a literature review, MIS quarterly, 26(2), XIII-XXIII.

WEEE, 2003, Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003.

Wei, S., Tang, O. and Liu, W., 2015, Refund policies for cores with quality variation in OEM remanufacturing. International Journal of Production Economics, 170(B), 629–640.

Whitehouse, G.E. and Pritzker, A.B., 1969, GERT: graphical evaluation and review technique, pt. 2, applications, AIIE Transactions, 1(1), 45-50.

Wikner, J., Towill, D.R. and Naim, M.M., 1991, Smoothing supply chain dynamics, International Journal of Production Economics, 22(3), 231–248.

Wolf, J., 2008. The nature of supply chain management research, Frankfurt: GablerVerlag.

Wu, Y.C.J. and Cheng, W.P., 2006, Reverse logistics in the publishing industry: China, Hong Kong, and Taiwan, International Journal of Physical Distribution & Logistics Management, 36(7), 507-512.

Xie, J.P., Ren, Y. and Zhao, Z., 2007, Research on stochastic disassembly network, Journal of Management, 4(2), 174–17.

Ye, F., Zhao, X., Prahinski, C. and Li, Y., 2013, The impact of institutional pressures, top managers' posture and reverse logistics on performance—

Evidence from China, International Journal of Production Economics, Elsevier, 143(1), 132–143.

Zhang, X.L., Potter, A., Naim, M., 2008. Uncertainty and reverse logistics decision making: a critical review. Proceedings of the 15th International Annual EurOMA Conference, University of Groningen, Netherlands, 15-18 June 2008.

Zhou, L. and Disney, S.M., 2006, Bullwhip and inventory variance in a closed loop supply chain, OR Spectrum, 28(1), 127–149.

Zhou, L., Disney, S. and Towill, D.R., 2010, A pragmatic approach to the design of bullwhip controllers. International Journal of Production Economics, 128(2), 556–568.

Zhou, L., Xie, J., Gu, X., Lin, Y., Ieromonachou, P. and Zhang, X. 2016 Forecasting return of used products for remanufacturing using graphical evaluation and review technique. International Journal of Production Economics, 181(B), 315-324.

Zhu, Q., Sarkis, J., Cordeiro, J. and Lai, K., 2008, Firm-level correlates of emergent green supply chain management practices in the Chinese context, Omega, 36(4), 577–591.

Zhu, Q. and Liu, Q., 2010, Eco-design planning in a Chinese telecommunication network company: Benchmarking its parent company. Benchmarking: An International Journal, 17(3), 363–377.

Zhu, Q., Sarkis, J. and Lai, K., 2008, Green supply chain management implications for “closing the loop.” Transportation Research Part E: Logistics and Transportation Review, 44(1), 1–18.