A Systems Dynamics Investigation Into The Impact Of Capacity Limitations On The Bullwhip Effect In A Closed-Loop Supply Chain With Remanufacturing

by

Locadia Linda Tombido

Dissertation presented for the degree of
Doctor of Philosophy in Engineering (Industrial Engineering)
in the Faculty of Engineering at Stellenbosch University

Supervisor: Prof L. Louw
Co-supervisor: Dr J. van Eeden

December 2019

Declaration

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Signature:

Date:

Abstract

This dissertation extends the concept of the 'bullwhip effect' by introducing sustainability issues and non-linear supply chains with capacity limits. Introducing a reverse supply chain complicates the supply chain dynamics as the reverse chain is known to be uncertain in terms of timing, quantity and quality of the product returns. This has an impact on inventory management policies and orders placed by the different echelons of the supply chain. The dissertation analysed the impact of factors such as the residence time, remanufacturing capacity and the reprocessing time on the Bullwhip effect in the closed loop system. The impact of these factors was further investigated when collection and remanufacturing capacity limits were introduced in a system where a remanufacturer had to collect enough products before remanufacturing begins. The system was first investigated without any capacity limitations and then the capacity limitations were introduced in each new scenario. Introducing collection and remanufacturing capacity limits introduced collection backlogs, remanufacturing backlogs and remanufacturing downtimes to the closed loop system. By adopting systems dynamics and case study approaches, the dissertation performed 'what-if' and sensitivity analyses of the closed-loop system under different levels of the factors under investigation. Two case studies were investigated one remanufacturing electric vehicle batteries (low demand, slow moving item) and the other remanufacturing kitchen appliances (high demand, fast moving item). The results confirmed the findings by previous researchers that introducing product returns to an existing forward chain reduces the Bullwhip effect of all levels of the supply chain. The Bullwhip effect further decreased with a decrease in residence time and an increase in remanufacturing percentage.

The research also had some new findings. Firstly, introducing collection and remanufacturing capacities for a closed-loop system where a company had to collect enough products before remanufacturing begins not only introduced collection and remanufacturing backlogs in the reverse chain, but it had different impacts depending on the product demand size and speed. Secondly, for both products, introducing capacity limits in a situation where a company has to collect enough products before remanufacturing begins led to an increase in the Bullwhip effect in the closed-loop system. Thirdly, slow moving items were not impacted by remanufacturing capacity limits and in the presence of both collection and remanufacturing capacity limits, it is better to collect more products than the remanufacturing capacity than it is to collect less products than the remanufacturing capacity. Fourthly, the presence of external returns by other parties not regulated by an organisation had an impact of lowering the Bullwhip effect in the closed-loop system and it also impacted how the other factors under investigation affected the Bullwhip effect. Finally, for fast moving items, it is better to delay remanufacturing due to a too small number of products being collected than it is to collect more products and keep them at the remanufacturing stations as remanufacturing backlogs. These findings were used to provide different managerial insights that could be useful for organisations venturing into reverse logistics. It is beneficial for a remanufacturing organisation to also collect and remanufacture products from other companies as the flow of external returns is not impacted by factors such as residence time. External returns in the reverse chain improve system dynamics by reducing the bullwhip effect in the closed loop system. In considering capacity expansion policies such as outsourcing, managers should consider the size of the demand of their product and the speed

with which the product disappears from the shelves since slow moving items are not affected by capacity limits in a similar way that fast moving items are.

Opsomming

Hierdie proefskrif verdiep die begrip oor die impak van die Sweepslag-effek op voorsieningskettings deur volhoubaarheidskwessies en nie-lineêre voorsieningskettings met kapasiteitsbeperkings te ondersoek. Die instelling van 'n omgekeerde voorsieningsketting bemoeilik die dinamika van die voorsieningsketting, aangesien die omgekeerde ketting heelwat meer onsekerhede bevat rakende die tydsberekening, hoeveelheid en kwaliteit van terugkerende produkte. Dit het 'n invloed op voorraadbestuurbeleide en bestellings wat deur die verskillende echelons van die voorsieningsketting geplaas word. Hierdie proefskrif het die impak van faktore soos die verblyftyd, hervervaardigingskapasiteit en die herverwerkingstyd op die Sweepslag-effek in die geslote lus-stelsel ontleed. Die invloed van hierdie faktore is verder ondersoek deur beperkings in die kapasiteit van versameling en hervervaardiging van terugkerende produkte in te stel in 'n stelsel waar 'n hervervaardiger eers genoeg produkte moes versamel voordat die hervervaardiging kon begin. Die stelsel is eers ondersoek sonder enige kapasiteitsbeperkings, en daarna is die kapasiteitsbeperkings in elke nuwe scenario ingestel. Deur versameling en hervervaardiging kapasiteitsbeperkings in te stel, word versameling agterstande, hervervaardiging agterstande, asook hervervaardiging stilstandtye in die geslote lusstelsel ingebring. Deur die gebruik van stelseldinamika en gevallestudiebenaderings, het die proefskrif 'wat-indien' en sensitiwiteitsanalises van die geslote lusstelsel uitgevoer onder verskillende vlakke van die faktore wat ondersoek word. Twee gevallestudies is ondersoek: een hervervaardig batterye vir elektriese voertuie (lae aanvraag, stadig bewegende item), en die ander hervervaardig kombuistoestelle (hoë aanvraag, vinnig bewegende item). Die resultate het bevindings van vorige navorsers bevestig dat die terugkering van produkte na 'n bestaande voorwaartse ketting die Sweepslag-effek van alle vlakke van die voorsieningsketting verminder. Die Sweepslag-effek het verder afgeneem met 'n afname in verblyftyd en 'n toename in die hervervaardigingspersentasie.

Die navorsing het ook 'n paar nuwe bevindings gehad. Eerstens het die versameling en hervervaardiging van 'n geslote lusstelsel, waar 'n maatskappy genoeg produkte moes versamel voordat die hervervaardiging kon begin, nie net versamel- en hervervaardigingsagterstande in die omgekeerde ketting aangebring nie, maar dit het verskillende gevolge gehad, afhangende van die grootte van die produk en die spoed daarvan. Tweedens het die invoering van kapasiteitsbeperkings in 'n situasie waar 'n maatskappy genoeg produkte moet versamel voordat die hervervaardiging begin, tot 'n toename in die Sweepslag-effek in die geslote lus gelei. Derdens, stadig bewegende items is nie beïnvloed deur hervervaardiging kapasiteitsbeperkings nie, en in die teenwoordigheid van beperkings in beide die kapasiteit van versameling en hervervaardiging, is dit beter om meer produkte as die hervervaardigingskapasiteit te versamel as minder. Vierdens het die aanwesigheid van eksterne terugkomste deur ander partye wat nie deur 'n organisasie gereguleer is nie, die Sweepslag-effek in die geslote lusstelsel laat daal, en dit het ook 'n invloed gehad op hoe die ander faktore wat ondersoek is die Sweepslag-effek beïnvloed. Laastens, vir vinnig bewegende items, is dit beter om die hervervaardiging te vertraag as gevolg van 'n te klein aantal produkte wat versamel word, as om meer produkte te versamel en dit by die hervervaardigingsstasies te hou as agterstande vir die vervaardiging daarvan. Hierdie bevindings is gebruik om verskillende bestuursinsigte te lewer wat nuttig kan wees vir organisasies wat terugkerende logistiek wil beoefen. Dit is voordelig vir 'n hervervaardigingsorganisasie om

ook produkte by ander ondernemings te versamel en te hervervaardig, aangesien die vloei van eksterne opbrengste nie beïnvloed word deur faktore soos verblyfstyd nie. Eksterne opbrengste in die omgekeerde ketting verbeter die dinamika van die sisteem deur die Sweepslag-effek in die geslote lusstelsel te verminder. By die oorweging van beleid oor die uitbreiding van kapasiteit (soos die gebruik van uitkontraktering), moet bestuurders die grootte van die vraag na hul produk en die spoed waarmee die produk van die rakke verdwyn, oorweeg. Dit is nodig aangesien stadig bewegende items anders beïnvloed word deur kapasiteitsbeperkings as vinnig bewegende items.

Acknowledgements

I would like to thank my academic supervisors, Professor Louis Louw and Doctor Joubert van Eeden for their support and encouragement. This work would not have been a success without their constructive criticism, motivation and support. “Baie dankie”.

In addition, I would also like to thank my field supervisor, Professor Suhaiza Zailani who managed to spare some days off her busy schedule to help me in finding and visiting some possible case studies for the research. '“Terimah kasih sangat ibu”.

I would also like to thank the examiners for taking time to read and critic my work. Your contribution has been a crucial part of my development as an Industrial Engineer. Thank you very much!

I would like to thank my colleagues, Rodney, Marianca, Nicholas and Marko for keeping me company and encouraging me. Karina, for believing in me, Anel for the support and finally Konrad for pushing me harder.

Finally, I would like to thank the Stellenbosch Industrial Engineering department for a wonderful 3 years and the warm welcome.

Thank you very much! God bless you all!

Table of Contents

List of Figures

List of Tables

List of Acronyms

BWE	Bullwhip Effect
CLSC	Closed-loop Supply Chain
DI cover time	Distributor inventory cover time
DI adjustment time	Distributor inventory adjustment time
OEM	Original Equipment Manufacturer
OUT	Order Up To
POS	Point of Sale
RI cover time	Retailer inventory cover time
RI adjustment time	Retailer inventory adjustment time
RL	Reverse Logistics
3P	Third-party
3PL	Third-party Logistics Provider
3PRLP	Third-party Reverse Logistics Provider
WEEE	Waste Electrical and Electronic Equipment
WI cover time	Wholesaler inventory cover time
WI adjustment time	Wholesaler inventory adjustment time
WIP	Work in Process

Glossary

Collection capacity limits	The maximum number of used products that an organisation could collect per unit time.
Collection percentage	The percentage of used products that the company managed to recover from customers.
Inventory adjustment time	The time taken to correct inventory discrepancies due to changes in demand.
Inventory cover time	A level of extra stock that was maintained to mitigate risks of stock out. It was the length of time that the inventory could last given current usage.
Remanufacturing backlogs	The number of orders stocked and in queue to be remanufactured. They usually appeared when the company failed to collect enough products to begin remanufacturing and had to stock collected products until they had enough or when the company collected products that were more than the remanufacturing capacity and the extra products had to be carried over to the next period.
Remanufacturing capacity limits	The minimum number of used products that a company had to collect per unit time for it to be able to begin remanufacturing. It was also the maximum number of used products that a company could remanufacture per unit time.
Remanufacturing downtime	The periods of time when there was no remanufacturing taking place. This was mostly because the company had failed to collect enough products to begin remanufacturing in that period.
Remanufacturing percentage	The percentage of collected used products that were inspected and found to be remanufacturable.
Remanufacturing lead time	The time from which a product was sold until it returns to the serviceable inventory. It was made up of the residence time, dismantling time, inspection time and the disposition time.
Reprocessing time	The time it took to remanufacture a used product.

Residence time	The time that the customer kept the product before returning it for remanufacturing.
Reverse logistics	The process of planning, implementing and controlling the efficient, cost effective flow of raw materials, in process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing or creating value or proper disposal.

CHAPTER 1
INTRODUCTION

The 'bullwhip effect' (BWE) in supply chains is a common phenomenon that changes with the introduction of reverse logistics in a supply chain. The impact of reverse logistics on the supply chain is thought to change when collection and remanufacturing capacity limits are introduced to the Closed-loop Supply Chain (CLSC). The research involved two organisations from different remanufacturing sectors to investigate the impact of remanufacturing and collection capacity limits on the bullwhip effect. This enabled the establishment of the impact of factors such as remanufacturing capacity, collection capacity and lead times on the performance of closed-loop supply chains.

The following concepts were presented in this dissertation;

- An analysis of the bullwhip effect in both traditional forward and closed-loop supply chains.
- A study of reverse logistics and the impact of different factors on the performance of a closed-loop supply chain.
- An analysis of modelling techniques for closed-loop supply chains based on their complexities and uncertainties.

This chapter introduces the concepts of reverse logistics and closed-loop supply chains and explains the goals and setup of the dissertation. Section 1.1 provides the background and rationale of the research. Section 1.2 describes the research problem statement and questions. The research objectives are described in Section 1.3. Section 1.4 justifies the research. Section 1.5 discusses the research design and Section 1.6 mentions the research methodology. The limitations and delimitations of the research are explained in Section 1.7. Section 1.8 details the ethical implications and Section 1.9 provides the outline of the rest of the dissertation.

1.1 Background and rationale of the research

Le Blanc (2006) mentioned a shift in power in the supply chain from the manufacturer and suppliers to the end customer. This shift has led to an introduction of various demands and technologies in the supply chain. Supply chain management is important in creating competitive advantage through the integration of supply chain partners to create a system that benefits the whole supply chain. Because of the changing business environment, supply chain management has become a competitive force, with most organisations engaging their suppliers and customers in the supply chain processes. This competitive advantage is only possible through visibility in the supply chain which is achieved through information sharing. Companies need to consider their partners in order to ensure consistency in supply, cost reduction as well as to explore some innovations that have never been explored before, in addition to utilising different capabilities by different partners.

As much as most companies now focus on integrated supply chains, Simchi-Levi, Kamnsky, and Simchi-Levi (2008) mentioned that uncertainties are always an inherent part of the supply chain. The ever-changing customer needs and responses have introduced uncertainties in the supply chain. Organisations are struggling to keep up with these rapid changes. These rapid changes result in unstable and volatile demand patterns in the supply chain. The problem is worsened when players in the supply chain fail to communicate changes and they panic when reacting to such patterns. Changes like this not only impact one player in the chain but they affect the whole supply chain and losses are experienced.

The bullwhip effect was identified by Lee, Padmanabhan, and Whang (1997) as one of the problems that comes about because of the inaccuracies of forecasting techniques. This is particularly true when a supply chain is not globally optimised and there is no information sharing. A clear picture of the bullwhip effect was obtained from the case of Procter & Gamble as explained by Lee et al. (1997). The paper explains how Procter & Gamble examined the demand patterns of their best-selling product, Pampers, and noticed that sales at retail stores were fluctuating but the variabilities were not that excessive. A look at the distributors revealed even greater variabilities and orders for materials from suppliers such as 3M showed that these variabilities continued to increase. While the demand for diapers was steady, the demand variabilities were amplified as one moved upstream. A very impressive demand fluctuation was found at the Barilla plant for pasta when demand for pasta in Italy was very flat with very minor seasonal fluctuations as explained by Zotteri (2013).

Given that variability in any form is problematic for effective operations, it is clear that the bullwhip effect is not a desirable phenomenon. Lee et al. (1997) explained the consequences of the bullwhip effect in the supply chain, stating problems such as excessive inventory investment, poor customer sales leading to loss of sales, misguided capacity plans, inactive transportation and missed production schedules. All these result in excess costs which would impact on the supply chain's profitability.

Wang and Disney (2015) observed how the BWE is taking other forms and has expanded from just customer orders to labour, machine utilisations and supply chain costs. This shows that as a phenomenon, no matter how long it has been studied, it is still of particular interest both to academia and industry. Studies on the bullwhip effect have evolved from measurement and quantification to mitigation and currently they are expanding to the service industry and sustainability issues.

Because most organisations focus on reducing the bullwhip effect through information sharing, there is definitely no room for any form of uncertainty that can lead to an increase in this phenomenon in a supply chain. However, in the process of integrating partners in the supply chain, some processes have been introduced into the supply chains which increase risk. For example Simchi-Levi et al. (2008) explained how the process of outsourcing functions within a supply chain increases the risk of product recall. This risk introduces yet another uncertainty in the supply chain, namely that of product returns.

In addition to this risk, products with shorter life cycles have also emerged and these pose a threat to the environment. These products have led to the unpopularity of the forward supply chain as different supply chains try to maintain their goodwill through caring for the environment. It is from this concept that the idea of product returns emerged. Fleishmann (2000) mentioned the most common drivers of reverse logistics which include:

- Reverse inbound flows may be economically attractive since used or returned products represent cheap resources from which value may be recovered.

- Market triggers refer to the role of reverse logistics in improving a company's market position that is setting up a 'green profile'.
- Environmental regulation, for example the 'White and Brown Goods Act' in the Netherlands obliges manufacturers and importers of electronic appliances to take back their products after use and recover certain minimum percentages.
- Asset protection whereby companies try to prevent sensitive components from leaking to secondary markets or competitors.

For some companies, however, returns are part of the business and they are an inherent part of their supply chain. An example of this is popular in apparel where fashion is sold online with the option of customers returning clothes when they are not satisfied with the quality or if the size is not right. Returnable pallets and containers have always defined the reverse supply chain for years. As a result of these drivers, it is necessary to study the concept of reverse supply chains both from a technical and economical perspective.

Returns in the supply chain present uncertainties in terms of their quality and their flow back into the forward chain. While the concept of returns may be viewed by some managers as a problem, some companies use the concept of reverse logistics as an indispensable part of new businesses. As mentioned by Domgala and Woliniak (2013), one such company is Bosch which has made a profitable business by selling remanufactured tools. In addition, the company is a leading supplier of industrially remanufactured products such as starters, alternators and other components. However, the question still arises as to whether the presence of the reverse flow in a supply chain will increase the bullwhip effect which is already a problem for most managers, according to Lee et al. (1997).

Research has been done on the bullwhip effect in closed-loop supply chains. Based on the methodologies and assumptions used by each author in this research, different conclusions have been reached, most of which have been conflicting. Cannella, Bruccoleri, and Framinan (2016) argued that all the studies on the BWE in closed-loop supply chains differ in terms of assumptions, parameters and research methodology and thus results are not really comparable. They mention differences in modelling, such as the number of echelons of the supply chains, final customers' demand pattern, assumptions regarding the inventory and quantity of the order and the availability of information on the flow of returns.

Although most of the studies have differed in their modelling assumptions, there have been some assumptions that have been used by almost all of the authors in modelling the BWE in closed-loop assumptions. One such assumption was that there is no limit to the remanufacturing capacity and returns are remanufactured as soon as they enter the reverse flow. This is not usually applicable in the real world as many organisations are said to face problems in remanufacturing capacity management (Heydari, Govindan,& Sadeghi 2018). The authors argue that a stochastic remanufacturing capacity is typical in many real case studies such as cell phone and electronic device industries.

Remanufacturing capacity may fluctuate because of machine breakdowns, irregular supplies of cores and the sharing of capacity between different products. Although the problem of remanufacturing capacity management has been looked into by some authors (as explained in the literature review in Chapter 2), most authors focused on capacity management and expansion alternatives for organisations that shared manufacturing and remanufacturing capacity. For those authors that focused on split capacity between manufacturing and remanufacturing, the main focus was on finding the optimal capacity limits to maximise profit.

Up until now, there has been very limited literature focusing on the impact of collection and remanufacturing capacity on the BWE in closed-loop supply chains. The only available article was by Adenso-Díaz, Moreno, Gutiérrez, and Lozano (2012). The authors claimed that the recycler's remanufacturing capacity limit had no significant impact on the BWE in a closed-loop system. However, their result was based on simulation runs using the cider game where the reverse channel did not look at other activities of the reverse supply chain such as collection, which might also have limited capacities. Recently, Dominguez, Ponte, Cannella, and Framinan (2019) investigated the impact of manufacturing and remanufacturing capacity limits on supply chain limits. Their conclusion was that the capacity limit in the remanufacturing line may enable the reduction in the BWE suffered by the manufacturer. Their results did not agree with those of Adenso-Díaz et al. (2012). However, the authors focused on a single echelon supply chain and they did not consider capacity limits in more than one activity of the reverse supply chain.

This dissertation investigated the impact of having fixed collection and remanufacturing limits on the BWE in a closed-loop system. Dominguez et al.(2019) described capacity constraints as, "a consideration of upper limits in the order sizes placed by suppliers, or upper limits in the orders' acceptance channel". This dissertation defines a lower and an upper limit in the orders' acceptance channel as it limits both the collected and the remanufactured products in the closed-loop system. Poles and Cheong (2011) stated that a limited system capacity can affect the efficiency of a production and inventory system for remanufacturing. These inefficiencies in production and inventory may have an impact on the BWE through an increase in both manufacturing and remanufacturing lead times. Because of the limitations in the case studies available, only the concepts of remanufacturing and reuse were investigated. An example of previous research on the BWE in closed-loop supply chains was by Das and Dutta (2013) whereby system dynamics was used to investigate the impact of the rate of product returns especially for recycling, remanufacturing and reuse on the BWE in the forward chain. A product exchange policy was introduced to influence the rate of returns. The authors concluded that the increase in the rate of return reduced the BWE under the assumption of unlimited remanufacturing capacity. It is this conclusion that has been reached by most authors that will be used as the initial hypothesis of this research as will be explained in developing the model.

Das and Dutta (2013) focused on a closed-loop system whereby the manufacturer was responsible for all reverse logistics activities. Adenso-Díaz et al.(2012) investigated the impact of the recycler's capacity on the BWE and concluded that it had no impact. This research seeks to explore the impact of the presence of collection and remanufacturing capacity limits in reverse logistics. Heydari, Govindan, and Sadeghi (2018) further explained that when there is a limited capacity for the remanufacturing of products, too many returns may cause inefficiency in the reverse system. In a similar fashion, when there is sufficient capacity, an insufficient supply of product returns causes downtime in the remanufacturing capacity and this downtime results in inefficiencies in the reverse system. Because of these arguments, this dissertation seeks to use case studies in experimenting on the impacts of introducing collection and remanufacturing capacity limits on the BWE in a closed-loop system.

1.2 Research problem statement and questions

1.2.1 Problem statement

When introducing a reverse supply chain to an existing forward chain, the costs, benefits and profits are always the major concerns for decision-makers even though they are not the major drivers of reverse logistics. The essential questions on the implementation of reverse logistics include:

- Why is it necessary to introduce reverse logistics to an existing supply chain?
- How does an organisation introduce and match the processes of a reverse network to those of an existing forward network?
- How beneficial will this network be to an existing business?
- How are resource limits going to affect the performance of the reverse logistics system?

Various reasons have been identified as to why most supply chains are incorporating the reverse chain and some of them have no option because of environmental laws. The question, *"How are resource limits going to affect the performance of the reverse logistics system?"* has been investigated by various organisations involved in reverse logistics and closed-loop supply chains. However, they have focused mostly on capacity management through expansion and contraction. Existing examples and case studies have not brought about any clarification on the implications of capacity limits on the reverse chain. The issue has not been explored in terms of both performance measurement and managerial implications. Therefore, the answers to "*How to introduce and match the processes of a reverse network to those of an existing forward network?"* and *"How is performance of the reverse logistics networks going to be affected by resource limits?"* may exist but are not clearly explained and defined for most reverse logistics processes.

In order to support the decisions made for selecting the operating modes and channels in a reverse logistics system, performance has to be measured and benefits and drawbacks of using various channels established based on performance. The measurement of the BWE helps to identify excessive inventory costs, production planning and inventory management issues with regard to reverse logistics and how collection and remanufacturing capacity limits may contribute to such issues. A comparison of BWE measures among different operating channels in closed-loop supply chains should assist in explaining the challenges and benefits of having capacity limits in the reverse supply chain to help in decision-making for companies aspiring to implement reverse logistics networks in their supply chains.

1.2.2 Research questions

The primary objective of this study was to measure the BWE in closed-loop supply chains and investigate how it was affected by capacity limits for both collection and remanufacturing of used products. Based on the research problems above, it specifically addressed the following questions:

- What is capacity and how is it specified in a closed-loop supply chain?
- How do capacity limitations impact the activities of the forward and reverse chain in the supply chain?

- How would the bullwhip effect and inventory variance in the forward chain be affected by introducing a reverse chain for either reuse or remanufacturing end-of-use products?
- How would the bullwhip effect and inventory variance ratio in a closed-loop supply chain change if the collection and remanufacturing capacities are limited?

The research questions and hypotheses are shown in Table 1.1. The hypotheses were derived from conclusions from previous research and also arguments based on disagreements by the author on conclusions reached by other authors on the topic.

The first and second hypotheses were drawn from Zhou and Disney(2006) which became the basis of most of the studies on the BWE in closed-loop supply chains. The third hypothesis is an argument presented by the author based on research presented by Adenso-Díaz *et al.* (2012) where they argue that the recycler's capacity has no impact on the BWE in a closed-loop supply chain.

1.3 Research objectives

The main objective of this research is to develop systems dynamics models to measure closed-loop supply chain performance and the BWE. To achieve this main objective, the following sub-objectives are defined:

1) **Defining collection and remanufacturing capacities** – exploring how collection and remanufacturing capacities are expressed within various organisations.

2) **Measuring the impact of capacity limits in reverse logistics** – identifying changes that occur in a closed-loop system when capacities have maximum upper limits.

3) **Comparing supply chain performance** between closed-loop systems that have capacity limits and those that do not.

1.4 Research contribution

This research contributed to the following topics of interest;

- Bullwhip effect in closed-loop supply chains
- Limitations in literature
- Suggestions for future practice

1.4.1 Bullwhip effect in closed-loop supply chains

Following the Waste Electrical and Electronic Equipment (WEEE) laws in the Netherlands, more and more Extended Producer Responsibility (EPR) laws are being passed for various products to encourage environmental protection from hazardous substances. Most organisations are incorporating the reverse supply chain, not only as a way of protecting the environment but also to protect their assets and because it is more economical. Reverse logistics appears to be growing in importance.

Table 1.1: Research questions and hypotheses

Research Question	Theoretical Propositions and Hypotheses
How is BWE affected by introducing a reverse supply chain into existing forward chain?	Depending on the case studies, the reverse supply chain can either be a remanufacturing, reuse, recycling or refurbishing reverse chain. **Theoretical Proposition 1** Increasing the remanufacturing lead time increases the BWE Hypotheses • Increasing the time that the product stays with the customer before being returned introduces material delays which will impact the BWE in the forward chain. • The more time it takes to carry out reverse logistics activities such as remanufacturing, collection and inspection, increases material delays which may increase the BWE in the forward chain. **Theoretical proposition 2** Increasing the remanufacturing percentage decreases the BWE Hypothesis • An increase in the amount of products accepted for remanufacturing or reuse can reduce variabilities in the component, raw material and retailer stock which may reduce the BWE in the forward chain.
How would the supply chain performance measures such as the BWE, and inventory stability in a closed loop system change if collection and remanufacturing have capacity limits?	Capacity limits exist in a supply chain because of existing resources and these have consequences on operations in the supply chain. **Theoretical Proposition 3** Capacity limits in terms of collection and disposition may lead to delays which can increase remanufacturing lead time and lead to an increase in the Bullwhip effect. Hypothesis • The remanufacturing capacity may be more or less than the collected products which may impact the period in which collected products are remanufactured, especially if the capacity is fixed.

In exploring the transformations in logistics over the next 15 years, Thatcher (2016) mentioned how reverse logistics, remanufacturing, 360-degree supply chains and other advanced recycling practices (such as the certified destruction of information systems or engineering bacteria to convert waste to useful materials) will expand. They explained the transition of ownership, as the customer also becomes the supplier. This observation explained the growing need for reverse logistics and its shift from being an option to becoming a necessity for most organisations.

Whilst the concept of reverse logistics has ceased to be an option but a necessity for some organisations, a need has arisen for most organisations to be able to align their benefits and profits from the reverse logistics business. In maximising profits and benefits, organisations try to minimise losses due to excessive inventory investment, poor customer sales leading to loss of sales, misguided capacity plans, inactive transportation and missed production schedules. All these result in excess costs which would impact on the supply chain's profitability. Most of these result from the BWE as explained by Lee et al. (1997). This research aims to draw attention to those factors of the reverse supply chain that impact the BWE in the supply chain.

The main audience for the research would be production and supply chain planners, operations managers, inventory management personnel and third-party logistics (3PLs) providers wishing to enter the reverse logistics business.

1.4.2 Limitations in literature

Although the BWE is an important phenomenon in supply chain management and has been looked into by many authors, Wang and Disney (2015) mentioned how the topic is being extended. In their invited review, the authors mention the BWE in sustainability issues and the BWE in non-linear and complex supply chains with capacity limits as some of the new and trending topics on the BWE. This dissertation investigates the BWE in closed loop supply chains. Although there are a lot of studies focusing on the forward chain, the same cannot be said for the BWE in closed-loop supply chains. Closed-loop supply chains present a challenge to most organisations in terms of implementation, especially to an already existing forward chain. They present challenges in terms of quality, timing and quantity of returns which makes it a problem in planning supply chain operations.

This research not only aims to add to literature, but it combines two of the extensions mentioned by Wang and Disney (2015) in investigating the concept of the BWE in supply chains. These two extensions are: 1. BWE and sustainability issues (represented by closed loop supply chains) and 2. BWE in complex non-linear supply chains with capacity limits (represented by collection and remanufacturing capacity limits in the reverse chain). Poles and Cheong (2011) mentioned that introducing capacity limits in modelling supply chains makes a system more realistic and more representative of real world scenarios. This will help any Original Equipment Manufacturer (OEM), Third-party Reverse Logistics Provider (3PRLP), or any organisation wishing to practice reverse logistics in knowing the impact of delayed remanufacturing and decide on capacity expansion decisions should they be necessary.

1.4.3 Suggestions for future practice

This research is expected to shed light on how the introduction of capacity limits into reverse logistics affected supply chain performance and the BWE. The findings of this research offer important managerial insights into assisting firms to decide on a better alternative of managing and handling an organisation's capacity limitations in reverse logistics activities should that become a necessity. The systems dynamics models represent various activities where capacity limits are more common and are actually tested on real organisations that will give benefits and feedback on each different operating mode.

The relaxation of the infinite collection and remanufacturing capacity assumption (as applied in this research) provides a more technical view than existing views of the concept of reverse logistics. It gives organisations focusing on these activities an idea of the consequences of their activities on variability and uncertainty in the supply chain. These areas have always been looked at from a profitability point of view. The research does not look at supply chain profits but used the BWE ratio as a performance measure of some policies on remanufacturing and product reuse. A focus on the impacts of capacity limits helps in capacity management decisions where organisations have to decide whether or not to expand capacity through activities such as subcontracting .This will help new entrants into the reverse logistics business and especially those that practise the business of reverse logistics as a way of complying with certain regulations.

1.5 Research design

This research took on a positivism approach as the researcher was more concerned with facts rather than impressions. Facts were gathered on the impact of capacity limits in reverse logistics without considering human feelings or thoughts on the issue. The main focus was on current practices in industry and it did not explore the issues of human resources and opinions. The development of hypotheses that were investigated through case studies and simulation to either credit or discredit theories developed by previous authors formed the basis of this research. The researcher did not have any impact nor were they impacted by the subject of the research. The research was based on replication and statistical analyses.

The starting point was when the researcher collected literature on the subject topic and identified conclusions by previous authors to develop propositions and hypotheses for further investigation through case studies and simulation. Simulation was selected because a representation and simplified model of a system was necessary. Simulation also enabled theoretical situations to be tested using a 'what-if' analysis which is a major concept of this research. Case studies were necessary to establish the base case scenarios and values of the type of organisations under study in the research.

Table 1.2 summarises the research questions, objectives and the various methods that were used to meet each objective and answer the major research questions.

Table 1.2 shows four main methods that will be used during the course of this research:

- Literature review, to identify research gaps.
- Systems dynamics to model a system where it is expensive to experiment with the real system.
- 'What-if' analysis to enable experimentation on a case under a different set of conditions.
- Statistical analysis to determine the significance and interactive effects of the factors under investigation.

Table 1.2: Research design

Research Questions	Research Objectives	Research Methods
How is the BWE in the supply chain affected by introducing a reverse supply chain into an existing forward chain?	Develop a systems dynamics model to measure closed loop supply chain performance and BWE.	1) Conduct a literature review to identify and suggest hypotheses 2) Develop a systems dynamics simulation model to measure supply chain performance and the BWE. 3) Conduct what if analysis under various scenarios and conditions. 4) Use statistical analysis to investigate the significance of factors and their interaction.
How would the supply chain performance measures such as the BWE and inventory stability in a closed loop system change if collection and remanufacturing have capacity limits?	Comparing supply chain performance between closed loop systems that have collection and remanufacturing capacity limits and those that do not.	1) Conduct a literature review to identify and suggest hypotheses 2) Develop a systems dynamics simulation model to measure supply chain performance and the BWE. 3) Conduct 'what-if' analysis under various scenarios and conditions. 4) Use statistical analysis to investigate the significance of factors and their interaction.

1.6 Research methodology/process

This research was within the field of reverse logistics and closed-loop supply chains, applying mathematical modelling and computer simulation to existing case studies.

As explained by Chaturvedi (2010), a model is a factual representation of reality. A mathematical model describes mathematically the properties and interactions in the system by means of variables. Modelling is necessary when it is impossible to carry out experiments on real-world systems because it is either too risky or too expensive.

Most mathematical models are usually executed using computer simulation. McHaney (2009) explained how, in computer simulation, a computer is used to imitate the operations of a real-world process based on defined logical, statistical or mathematical assumptions. Robinson (2004) explained situations in which computer simulation becomes useful;

- **Cost:** It is expensive to interrupt day-to-day activities in order to try out new ideas. Apart from the cost of making changes, it may be necessary to shut the system down for a period whilst the alterations are being made.

- **Time:** It is time consuming to experiment with a real system. It may take weeks or months before a true reflection of the performance of the system can be obtained.
- **Control of experimental conditions:** When comparing alternatives, it is useful to control the conditions under which the experiments are performed so direct comparisons may be made. It is difficult when experimenting with the real system.
- **The real system does not exist:** The real system may not yet exist and the only option would be to develop a model.

Mathematical modelling and simulation were used in this research as there were a lot of experiments based on 'what-if' analysis which would be costly and risky to ask organisations to experiment with their systems. Simulation was also necessary because closed-loop supply chains are not very common and one of the challenges in this research was finding case studies. In this case, simulation was used to conduct the 'what-if' scenarios where a case study was not present.

In addition to simulation and modelling, this research was also case study-based. A case study was defined by Yin (1994) as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and the context are not clearly evident". Stoecker (1991) explained that the case study is neither a data collection technique nor merely a design feature alone but a comprehensive research strategy. Yin (1994) mentioned the characteristics of a case study inquiry:

- Copes with the technically distinctive situation in which there will be many more variables of interest than data points and as a result;
- Relies on multiple sources of evidence with data needing to converge in a triangulating fashion and as another result;
- Benefits from the development of theoretical propositions to guide data collection and analysis.

This research attempted to investigate the impact of the presence of collection and remanufacturing capacities on closed-loop supply chains with consideration of variables such as remanufacturing lead time. Because a comparison was made, there was a need for at least two case studies, hence the multiple case study approach and the use of multiple sources of evidence. Theoretical propositions were developed once research questions had been defined and these propositions were based on previous literature and assumptions by the researcher.

A multiple case study approach with multiple units to make comparisons on supply chain performance was employed. The case studies were in no way related which made their supply chains independent. By using multiple units, the research aimed to investigate independent entities of the supply chain such as the inventories of the components, serviceable inventory, distributor inventory, retailer inventory and demand.

The case study approach had some aspects of surveys and experimentation. Chapter 4 thoroughly explains the case study design and the case studies involved in this research. The research served to answer 'what' exploratory question types with a goal of developing a hypothesis on the definitions of and management of capacity in reverse logistics and closed-loop supply chains. The other focus of the research were 'how' and 'why' explanatory questions which focus on dynamics of a supply chain and links between various parameters of the closed-loop system hence the need for case study research.

Yin (1994) mentioned that the research methods are not mutually exclusive. This meant that various methods can be included in the case study research. The same author mentioned that experimentation is used when "an investigator can manipulate behaviour directly, precisely and systematically". The fact that this research used simulation to conduct 'what-if' analysis meant that case study research was combined with experimental research as well. The case study approach was used mainly for base case values and for answering the initial questions of this research. This case study depended on direct observation concurrently with interviewing personnel directly linked to closed-loop supply chains. Chapter 3 fully explains the methodology selection of the research. The Research Methodology is schematically represented in Figure 1.1.

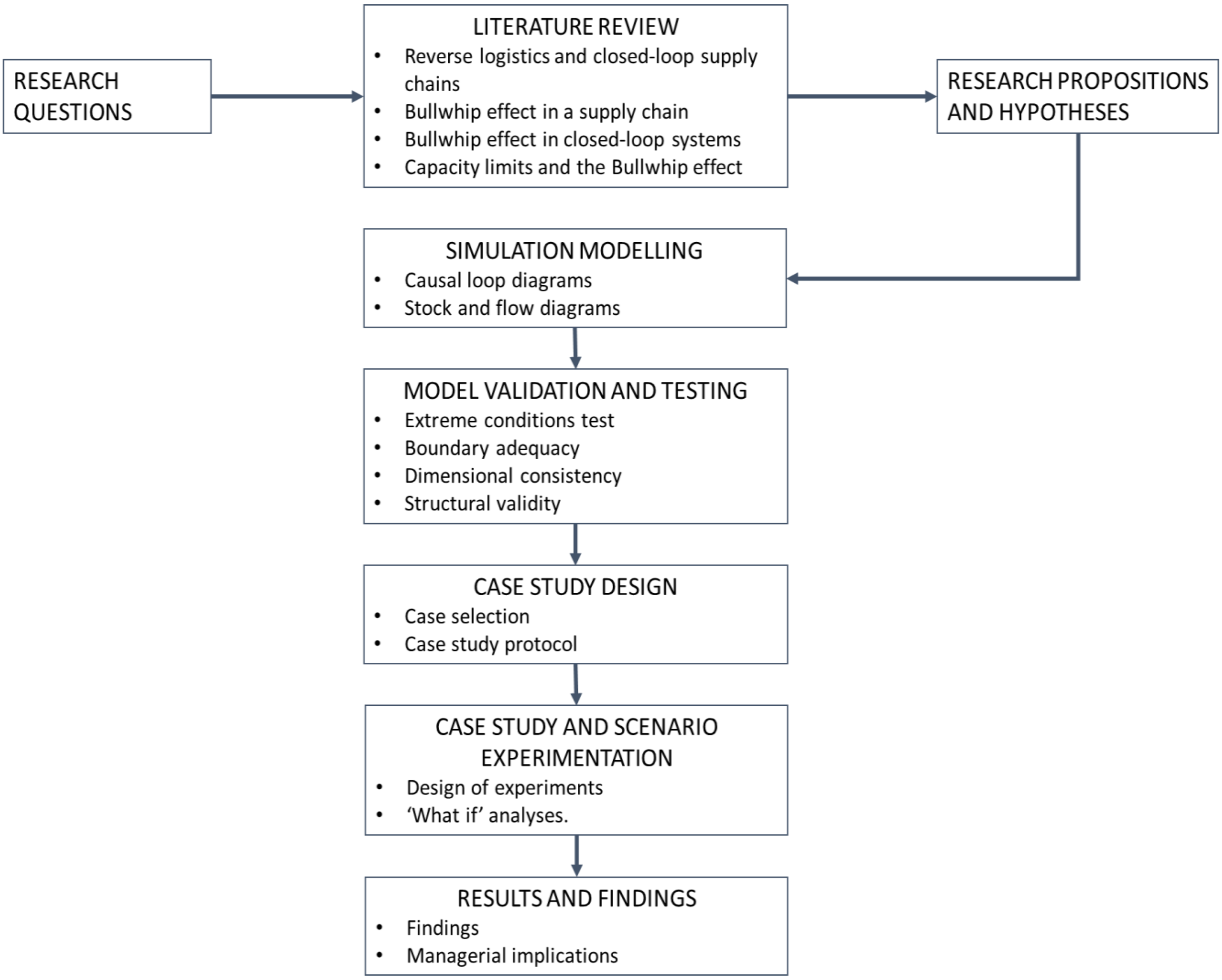


Figure 1.1: Research methodology outline

1.7 Delimitations and limitations

The dissertation studied closed-loop systems and the BWE in a supply chain from an operational perspective and it was purely technical. The study did not focus on supply chain profits or supply chain contracts between members of the closed-loop system. The dissertation also did not consider the behavioural causes of the BWE or any soft variables linked to human intuition.

It should also be noted that the dissertation did not study any capacity expansion policies in remanufacturing. It merely modelled a closed-loop system with collection and remanufacturing capacity limits. This led to backlogs in the reverse chain. It was assumed that the supply chain had no option to extend capacity, they operated on what they had. Although the collection percentage has been stated as one variable that had an impact on the BWE in a closed-loop system, it was not a factor under investigation in this dissertation as it was assumed that the organisation managed to collect all its used products.

The research was empirical and two case studies were used in the research. It should be noted however that, although the research was empirical, the participants were unwilling to provide historical information. This means that this research was based on average values and assumptions provided by the organisation and not by analysing historical demand patterns and data.

1.8 Ethical implications of the research

An ethical clearance for observing and interviewing the participants was obtained from the Ethics Commission of Stellenbosch University. However, the requirements for clearance letters from the organisation led to most of the organisations declining to participate and the researcher was left with only two case studies that agreed to participate.

1.9 Thesis outline

Figure 1.2 provides a schematic view of the structure of the dissertation. Chapter 1 introduced the reader to the aims and objectives of the research. Chapter 2 reviewed the available literature on the topic at hand and Chapter 3 focused on the selection of the suitable research methodology for the dissertation. In Chapter 4, the selected methodologies were discussed in more detail. Chapter 5 focused on the verification and validation of the simulation models. Chapter 6 carried out the policy and scenario experimentations of the systems dynamics models and Chapter 7 described the results, findings as well as the managerial implication of each of the findings. Chapter 8 provided an epilogue of the whole dissertation, providing the reader with future research directions. A summary of the whole thesis was provided in Chapter 9.

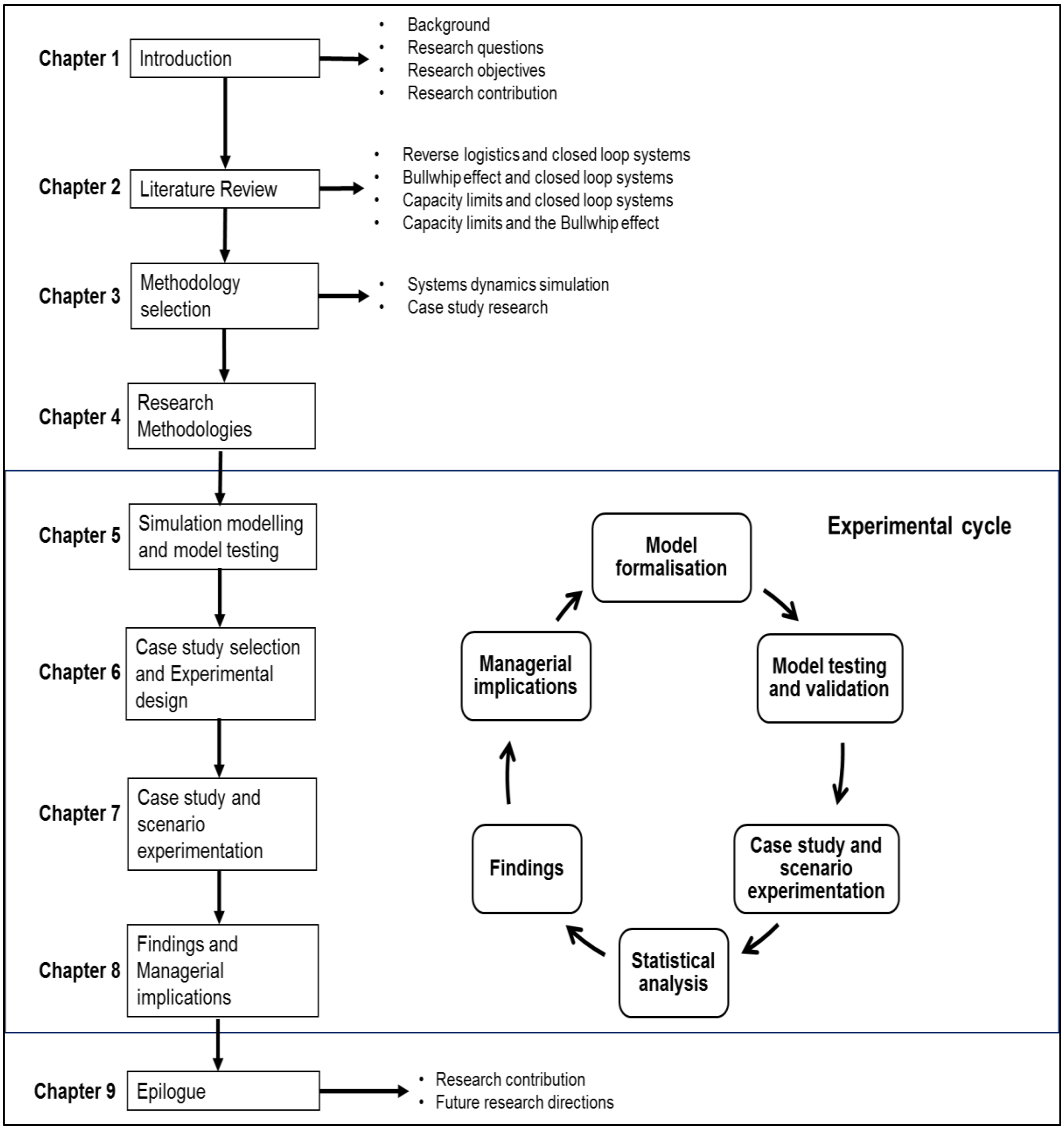


Figure 1.2: Thesis outline

CHAPTER 2
REVIEW OF RESEARCH PROBLEM

In this chapter, the research questions listed in Chapter 1 are used as the basis to understand terms and concepts discussed and to review the existing literature to support and analyse each subject. This research dealt with four major areas: (1) Reverse logistics, (2) Closed-loop supply chains, (3) Bullwhip effect and (4) Capacity constraints. In carrying out the review, the author mixed content analysis and systematic review. The chapter begins by explaining the philosophy of Supply Chain Management and the development of Reverse Supply Chains. The chapter then proceeds to differentiate between various reverse channels and the need for supply chain performance measurement in reverse supply chains. The chapter concludes by identifying gaps in the main topic of interest in this research.

2.1 Logistics and supply chain management

Le Blanc (2006) mentioned a shift in power in the supply chain from the manufacturers to the customers. Because of this shift, manufacturers are doing everything they can to meet customer demands in order for them to stay competitive and in business.

Mentzer, Keebler, Nix, Smith, and Zacharia (2001) defined a supply chain as “a set of three or more entities (organisations or individuals) directly involved in the upstream and downstream flows of products, services, finances and/or information from a source to a customer”. This clearly showed that a supply chain is not made up of one organisation but more than one organisation. The Global Supply Chain Forum further defines Supply Chain Management as “the integration of key business processes from the user through original suppliers that provides products, services and information that adds value to customers and other stakeholders”.

Ellram and Cooper (1990) explained the concept of Supply Chain Management as a philosophy that takes a systems approach to viewing the supply chain as a single entity rather than a set of fragmented parts, each performing its own function. The philosophy of Supply Chain Management is supposed to drive supply chain members towards customer orientation and extend the concept of partnerships into multiform effort. Ellram and Cooper (1990) further identify three characteristics of Supply Chain Management philosophy which include:

- A systems approach to viewing the supply chain as a whole, and to managing the total flow of goods inventory from the supplier to the ultimate customer.
- A strategic orientation towards cooperative efforts to synchronise and converge intrafirm operational and strategic capabilities into a unified whole.
- A customer focus to create unique and individualised sources of customer value, leading to customer satisfaction.

The expected benefits of Supply Chain Management are mentioned by Chang and Makatsoris (2002):

1. **Cycle time reduction** through the consideration of constraints as well as alternatives in the supply chain.
2. **Throughput improvements** through better coordination of material and capacity. This prevents loss of utilisation whilst waiting for parts.

3. **Inventory cost reductions through** demand and supply visibility. Demand and supply visibility lowers the requirement of inventory levels against uncertainty by achieving the ability to know when to buy materials based on customer demand, logistics capacity and the other materials needed to build together.
4. **Optimised transportation** achieved by optimising logistics and vehicle loads.
5. **Increased order fill rate** results from real-time visibility across the supply chain.
6. **Analysis of supply chain management** can help to predict the propagation of disturbance to downstream.
7. **Increase in customer responsiveness** as a result of understanding the capability to deliver based on the availability of materials, capacity and logistics.

Schneider-Maul (2017) emphasised that with the change in the bargaining power of customers nowadays, a supply chain has to be competitive. He lists the characteristics of competitive supply chains:

- **Innovative** as new technologies can create a competitive advantage if competitors lack these innovations and are thus less efficient.
- **Flexible** by being open-minded towards trends and change. This in turn creates an advantageous environment for the implementation of new technologies.
- **Proactive** by using new technologies such as predictive and preventive analytics to decrease the error potential and some problems are tackled before they even occur.
- **Transparent** supply chains have an increased visibility along all processes and for all supply chain partners. This helps in avoiding duplication of work, elimination of redundant data and increasing customer satisfaction.
- **Capable** in terms of technology and human abilities. This is necessary if a supply chain has to benefit from trends so as to be able to implement and use them effectively.

In trying to be competitive, supply chains have evolved over the years and each year panels of experts try to identify new trends in each upcoming era. Each era consists of new technologies and supply chain activities whilst other technologies and trends are either maturing, fast developing or declining. Each supply chain trend has a cycle which can be likened to a product life cycle.

The concept of Supply Chain Management has often been confused with Logistics Management and sometimes the terms have been interchanged especially when dealing with issues relating to product returns. The Council of Logistics Management argued in October 1998 that Logistics Management is only a part of Supply Chain Management and to cement their argument, they defined Logistics Management as "a part of the supply chain process that plans, implements and controls the efficient, effective flow and storage of goods, services and related information from the point of origin to the point of consumption in order to meet customers' requirements". In other words, Logistics Management mostly focuses on storage and flow of goods and information in the supply chain and it is concerned with issues such as transportation and warehousing.

In explaining the concepts of Supply Chain Management and Logistics Management, the Global Supply Chain Forum identified key supply chain processes which were further illustrated and explained by Lambert and Cooper (2000). Figure 2.1 shows an illustration of supply chain business processes.

The key supply chain processes are:

a. **Customer Relationship Management** involves identifying key customers or customer groups which the organisation targets as critical to its business mission. Customer service teams work with customers to further identify and eliminate sources of demand variability.

b. **Customer Service Management Process** provides the single source of customer information. It provides the customer with real time information on product shipping dates and product availability through interfaces with the organisation's production and distribution operations.

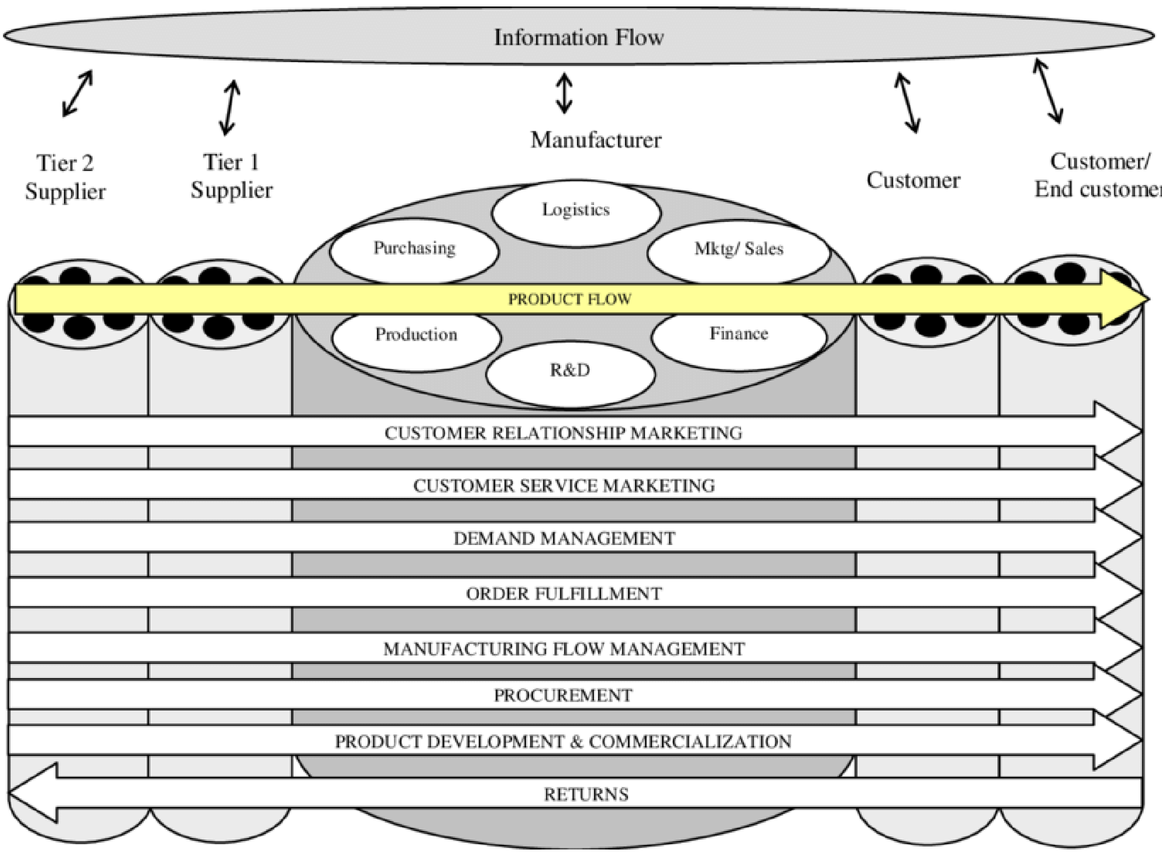


Figure 2.1: Supply chain business processes (Lambert & Cooper, 2000)

c. **Demand Management Process** must balance the customer's requirements with the firm's supply capabilities. A good demand management system uses point-of-sale and 'key' customer data to reduce uncertainty and provide efficient flows throughout the supply chain.

d. **Customer Order Fulfilment Process** has to meet customer need dates as it is important to achieve high order fill rates either on a line item or order basis.

e. **Manufacturing Flow Management Process** where the product is pulled through the plant based on customer needs. Manufacturing processes must be flexible to respond to market changes.

f. **Procurement Process** where strategic plans are developed with suppliers to support the manufacturing flow management process and development of new process.

g. **Product Development and Commercialisation** helps in making product development the lifeblood of a company's new products where new products are the lifeblood of the corporation. Customers and suppliers must be integrated in the product development process in order to reduce time to market. As product life cycles shorten, the right products must be developed and successfully launched in even shorter time frames in order to remain competitive.
h. **Returns Process** which if effectively managed enables identification of productivity improvement opportunities and breakthrough projects. Managing returns as a business process offers the same opportunity to achieve a sustainable competitive advantage as does managing the supply chain from an outbound process.

On the list of supply chain business processes is the concept of returns. It is this business process that was the main focus of this research.

2.2 Reverse logistics/Reverse supply chains

Drawing from the Council of Logistics Management's definition of logistics, Rogers (1999) in Rogers and Tibben-Lembke (2001) defined reverse logistics as "The process of planning, implementing and controlling the efficient, cost effective flow of raw materials, in process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing or creating value or proper disposal". Fleishmann (2000) argued that this definition excludes the flow of goods to specialised recovery companies such as independent remanufacturers and they define 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 direction for the purpose of recovering value or proper disposal".

This definition literally means that reverse logistics is concerned with the management of anything that goes in the opposite direction to the forward supply chain in the form of returns and that returns do not necessarily have to return to their point of origin or that returns do not necessarily come from the end customer only. It is this definition by Fleishmann (2000) that will be used throughout the course of this research. The term reverse logistics is sometimes interchanged with the term reverse supply chains. Bokade (2014) stated that a reverse supply chain occurs when customers return their purchases to retailers for refund, repair or a recall and an upstream movement of goods occurs from the retailer to the manufacturer. Although this research is meant to specifically focus on end-of-use customer product returns, the explanation by Bokade (2014) highlighted that reverse supply chains can exist from any type of returns. Therefore, it can be concluded that the reverse supply is not composed only of used products but any product that is returned upstream.

The study of closed-loop supply chains has evolved slowly over the years. Section 2.2.1 is specifically dedicated to explaining the evolution of Reverse Logistics and Closed-loop Supply Chain research in addition to highlighting some important discoveries and contributions to the topic. Some discoveries and contributions form the basis of this research.

2.2.1 The evolution of reverse logistics and closed-loop supply chain research

Guide Jr and Van Wassenhove (2009) explained the changes over the years in closed-loop supply chain research and emphasised that the phases in the evolution are not chronological, but different lenses applied by researchers over time. They explained five phases in the evolution of closed-loop supply chain research namely: Guide Jr and Van Wassenhove(2009) explained the changes over the years in closed loop supply chain research and emphasized that the phases in the evolution are not chronological, but different lenses applied by researchers over time. They explained five phases in the evolution of closed loop supply chain research namely:

1) The golden age of remanufacturing as a technical problem.
2) From remanufacturing to valuing of the Reverse Logistics process.
3) Coordinating the Reverse Supply Chain.
4) Closing the Loop.
5) Prices and Markets.

Phase 1: The golden age of remanufacturing as a technical problem

This was the phase in which the importance of remanufacturing as a process was neglected. In the US, early research was motivated by the need to make operations more efficient and to increase profitability of remanufacturing workshops whilst in Europe reverse logistics came about as a result of legislation. Researchers mainly focused on the disassembly operations. Popular authors in this phase included Bloemhof-Ruwaard, Van Wassenhove, Gabel, and Weaver (1996) who conducted research to determine if paper recycling reduced the environmental impact of the paper and pulp industry in Europe. They concluded that recycling offers a reduction in the environmental impact of the industry. De Ron and Penev (1995) focused more on European laws on discarded electronic consumer products and looked at disassembly options for the remanufacture of such products. Network design for a remanufacturing environment was looked into by Fleischmann (2001) when they presented a generic facility location model, at the same time discussing the differences from traditional logistics settings.

Guide Jr (1996) developed a schedule using Drum-Buffer-Rope method for a military depot and in 1998 the same author studied the creation and location of inventory buffers in a remanufacturing environment. According to Guide Jr and Van Wassenhove (2009), the key findings of this phase included;

- An understanding of the complicating characteristics of remanufacturing and reverse supply chains.
- The main activities and processes of the reverse logistics operation.
- The identification of different types of product returns with their specific impact on the reverse supply chain.

Based on these findings, Le Blanc (2006) identified and classified the main drivers of reverse logistics. The main classifications involved paradigm changes and individual drivers. The latter was further classified as business drivers and legislation. Figure 2.2 summarises the drivers as classified by Le Blanc (2006).

1. Paradigm changes

Le Blanc (2006) mentioned that, "the converging system of a series of interrelated processes, directed towards the consumer is being replaced by a network of processes aimed at optimizing the entire product life cycle." This shift was caused by several developments related to several types of value;

i. **Scarcity of resources** led to the need for a more careful use of resources. "Simultaneously, the demand for natural resources is increasing due to the industrial development in Asia"(Le Blanc, 2006).
ii. **Function selling or servicing** is defined as the process of selling product-based services instead of just the product. This involves the process of leasing products, making the manufacturer the legal owner of the product.
iii. **Increased product liabilities** due to the increasing power given to consumers. Consumers can now make demands and retailers are obliged to meet them due to technological changes and this results in product recalls and warranty claims. These liabilities have also been extended to the environment and they extend beyond warranty claims, as consumers expect functioning and safe products during the whole life cycle.

2. Individual Drivers

These drivers are divided into business opportunities and legislation. Legislation sometimes forces the implementation of reverse logistics while some organisations implement reverse logistics for profits as in the case of Bosch.

A. Business opportunities

i. **Economic gain** comes when the recovery of used products is cheaper than manufacturing new products from virgin materials. An example is the steel industry where scrap can be used to manufacture new products. Recovery of parts can also be cheaper, for example the single use cameras by Xerox.
ii. **Marketing** nowadays is accompanied by corporate and social responsibility statements as well as environmental responsibility as consumers become more and more environmentally conscious. Le Blanc (2006) mentioned the case when consumers boycotted Shell in 1996 since it wanted to dump their drilling rig, the Brent Spar into the sea. The boycott seriously harmed Shell's image and brand value.

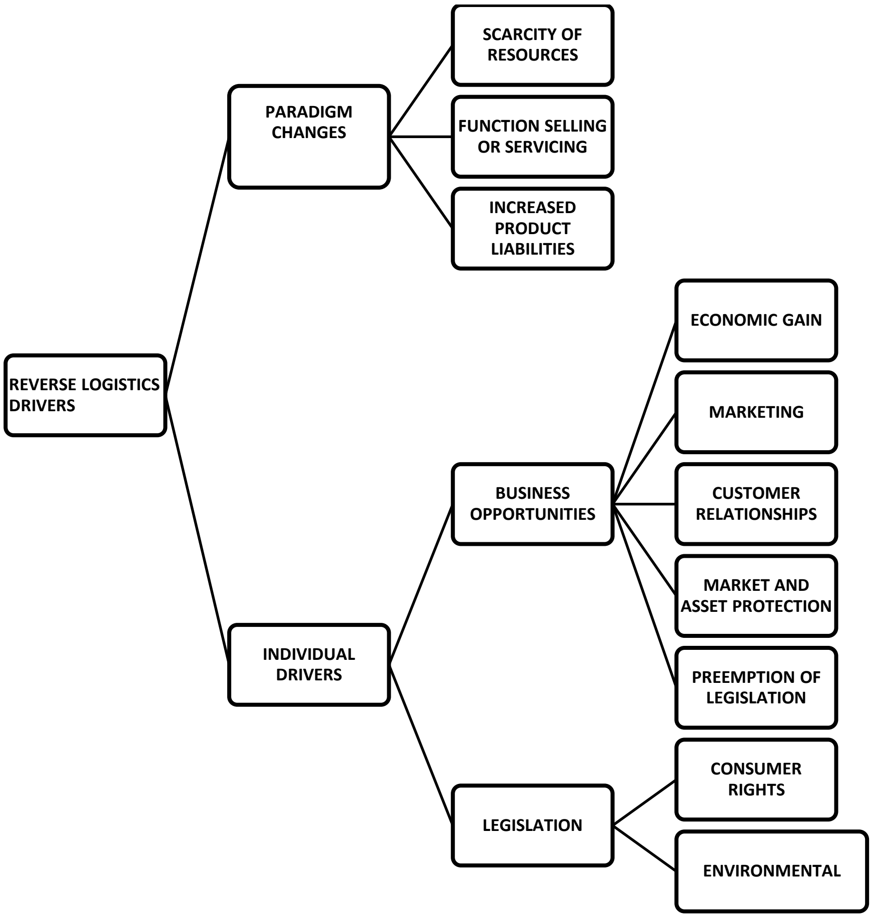


Figure 2.2: Summary of drivers of reverse logistics listed by Le Blanc (2006)

- **iii.** **Better customer relationships** for some specific businesses especially those that sell products online. The apparel industry is an example for such industries that permit returns of products when the customer is not satisfied with the quality or the size.
- **iv.** **Market asset protection** occurs when a company collects its product to prevent its technology from leaking to its competitors.
- **v.** **Pre-emption of legislation** happens when environmental legislation has not yet been implemented and a company voluntarily takes back its products to forestall or influence future legislation. Orsato (2002) mentioned the case of Renault, Peugeot and Citroen in France who collected their products to prevent direct regulation.

B. Legislation

- **i.** **Legislation protecting consumer rights** especially in Europe and the USA where customers are permitted to return a product within a specified time should they not be satisfied with the product or should they change their mind. Le Blanc (2006) mentioned the Directive 1999/44/EC that states that products that do not show the quality or performance the consumer can reasonably expect, given the nature of the goods, can be returned.
- **ii.** **Environmental legislation** mentioned by Toffel (2003) as having three basic goals of;
  - Reducing the amount of landfilled waste especially hazardous materials.
  - Increasing availability and lowering prices of recycled materials in comparison to virgin materials.

- Preventing pollution by the reduction of the environmental burden of end-of-life products at the source.

Most of these regulations are compulsory and the OEM has no alternative but to take back their products.

In addition to the drivers mentioned by Le Blanc (2006), Krikke, Le Blanc, and Van de Velde (2004) summarised the enforcers and enablers of reverse logistics as shown in Figure 2.3.

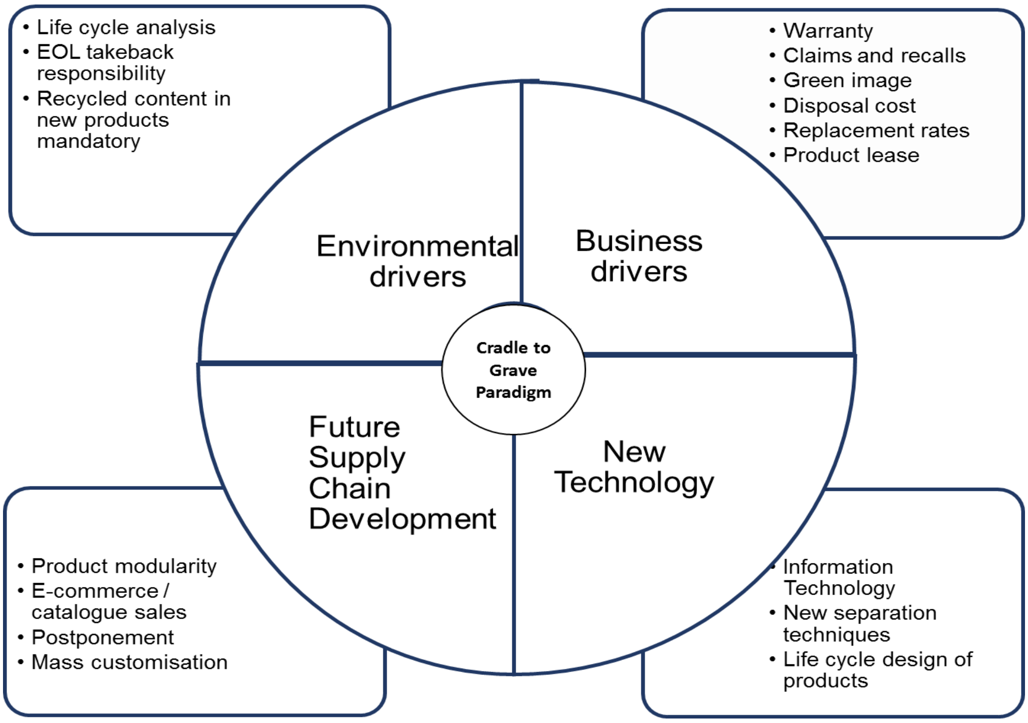


Figure 2.3: Enablers and enforcers of reverse logistics (Krikke *et al.*, 2004)

The bottom semicircle represents mostly the enablers (processes that support the concepts) of reverse logistics. Most of the future supply chain developments like product modularity, postponement and mass customisation support the concept of design for remanufacturing and design for reuse as organisations try to incorporate the concept of reverse logistics at the beginning when they are designing a product.

The enforcers are similar to the drivers mentioned by Le Blanc (2006).

While Le Blanc (2006) mentioned the drivers for the adoption of reverse logistics by organisations, de Brito and Dekker (2002) and Vasil (2011) classified the type of returns by customers. It should be noted that each stage is from a customer to the preceding stage in a supply chain. Table 2.1 summarises the classifications of returns by de Brito and Dekker (2002) and Vasil (2011).

Table 2.1: Classification of Product Returns by de Brito and Dekker (2002) and Vasil (2011)

Type of return	Description	Examples
Manufacturing Returns (production phase)		
Raw materials	• Raw materials may be left over as surplus during the production of a product.	Steel industry
Quality checks	• Products may fail quality checks after production and they have to be returned for reprocessing to produce new products	Casing of iron and steel
Production left overs	• Some products may be produced in excess and not part of the production plan and they are reworked to produce products that are needed that time.	Steel industry
Distribution returns (initiated by supply chain actor after manufacturing)		
Product recalls	• Product recollected because of safety or health problems with the products. • Usually initiated by the manufacturer or the supplier	• August 2006, Dell recalled 4.1 million lithium-ion batteries made by Sony due to several reports of laptop fires caused by the batteries.
Commercial returns	• Returns where the buyer has a contractual option to return products to the seller. • Wrong or damaged deliveries. • Unsold products that retailers and wholesalers return to manufacturers.	• Pharmaceuticals when products can no longer be sold.
Stock adjustments	• When an actor in the supply chain adjusts stock among warehouses and shops	
Functional returns	• The inherent function of a product makes it go back and forward in the chain.	• Distribution carriers in the form of pallets • Empty beverage bottles
Customer returns (initiated by customer after use)		
Warranty returns	• Customers return products that do not meet promised quality to get money or for repair.	• Warranty on most electronic products.
Repair/servicing	• Customer initiates a repair request on a product that has become non-functional or partially defective after the DOA period.	• Servicing of automobiles
End of use	• Situations where the user has an opportunity to return product at a certain life cycle stage	• Leasing cases • Returnable containers like bottles • Returns to second hand markets e.g. Bibliofind for Amazon

End of life	• Where products are at the end of their economic or physical life.	• electronics
Dead on arrival(DOA)	• Customer receives the product in a non-functional or partially defective state or the product becomes defective soon after purchase.	
Upgrade	• Customer surrenders the product because they wish to upgrade to the newest technology. The product may not be obsolete yet.	• electronics

The reverse supply chain is different from the forward chain. It comes with some uncertainties in terms of product quality and quantity, as well as the timing of the product returns. As a result, in addition to the usual forward chain activities, additional processes are necessary for the reverse supply chain. Blackburn et al.(2004) identified the following processes as necessary in the recovery of used products:

1. **Acquisition** is the process of obtaining the product from the customer and it is done in three different ways, (a) return of defective items by customer, (b) return of items from the waste stream when the customer has discarded the product or from an established reverse supply chain called a market driven system, (c) a market driven system is when the product is pulled upstream using various incentive alternatives such as deposits, and cash for product return. Das and Dutta (2013) emphasised this through the use of product exchange policy (offering customers new products in exchange for their old and worn out products to speed up the collection of waste products) in the reverse supply chain.
2. **Reverse logistics** refers to the modes of transport and distribution systems used in moving the returned products from the points of use to the points of disposition.
3. **Inspection and Disposition** has the objective of determining the level of quality of the returned product and an appropriate product recovery strategy for each product in the reverse supply chain. There are four main disposition alternatives according to Prahinski and Kocabasoglu (2006):

- Reuse means to immediately reuse or resell the product.
- Product upgrade, which is to repackage, repair, refurbish or remanufacture the product.
- Materials recovery, which includes cannibalisation (tearing down a product to obtain the useful components only) and recycling.
- Waste management which includes incinerating and land-filling the product.

4. **Reconditioning** is needed if the product upgrade or material recovery option is determined to be the most appropriate disposition strategy. The product is transferred to the reconditioning operation such as repair, refurbishing, remanufacturing and recycling.
5. **Distribution and sales** utilises a number of channels for the sale of refurbished products;

- Use of the same channel that is being utilised for new products while distinguishing between new and used products

- Selling the product to a specialty broker such as one that specialises in close out, job out, surplus or defective items within a particular industry. Products that are sold to brokers are typically resold to third parties, such as low-priced value retailers and consumers.

Phase 2: From remanufacturing to valuing the reverse logistics process

In this phase, researchers introduced two alternative ways of doing closed-loop supply chain research: (1) that of the classic operations research optimisation, and (2) the business management view. Under the business management view, there was a requirement to connect the sub-processes and explore reverse logistics from a business perspective. The business perspective provided road maps for new research fields in reverse logistics.

The first stage in the reverse logistics process is the acquisition and inspection of used products, yet it is the topic that has been given less attention. The business perspective explored such issues. Authors such as Guide Jr (2000) used a cell phone industry application to develop a framework for determining the optimal acquisition process and the corresponding profitability after varying the selling price. Similarly Aras, Boyaci, and Verter (2004) Similarly Aras, Boyaci, and Verter (2004) presented an approach for assessing the impact of quality-based categorisation of returned products claiming that the incorporation of returned product quality in remanufacturing and disposal decisions can lead to cost savings. Galbreth and Blackburn (2006) also focused on acquisition and inspection by deriving an optimal acquisition and sorting policy in the presence of used product variability for a remanufacturer facing both deterministic and uncertain demand.

From the business perspective, it was necessary to identify profitable disposition strategies depending on the condition of the used product. Disposition strategies were clearly explained by Thierry, Salomon, Nunen, and Van Wassenhove (1995). Table 2.2 clearly distinguishes among the known disposition strategies for returned products.

Table 2.2: Disposition strategies for returned products (Thierry *et al.*, 1995)

Options	**Operations**	**Level Of Disassembly**	**Quality Requirements**	**Resulting Output**	**Applied In**
Direct Reuse	Check on damage and clean.	Almost none	Restore product to working order.	As is e.g. refill	Original or similar markets.
Repair	Restore product to working order, some component repaired or replaced.	To product level	Restore product to working order.	Original product	Original or similar markets.
Refurbishing	Inspect and upgrade modules, some modules repaired or replaced by upgrades.	To module level	Inspect all modules and upgrade to a specified quality level.	Original product in upgraded version.	Original or similar markets.
Remanufacturing	Manufacture new products partly from old components.	To part level	Inspect all modules and restore to as new quality.	New product	Original or similar markets.
Cannibalization	Selective retrieval of components.	Selective retrieval of parts.	Depends on process in which parts are reused.	Some parts and component s reused and others scrapped.	Both original and alternative markets.
Scrap	Shred, sort, recycle, and dispose of.	To material level	High for production of original parts and less for other parts.	Material and residual waste.	Alternative markets

Reverse supply chains can either be classified as closed-loop supply chains or open loop supply chains. The concept of open and closed supply chains is determined by the product recovery strategy alternatives that organisations choose. Toffel (2003) summarised the various strategies in which organisations approach the concept of reverse logistics. Figure 4 shows a tree diagram that summarises the strategies as developed by Toffel (2003).

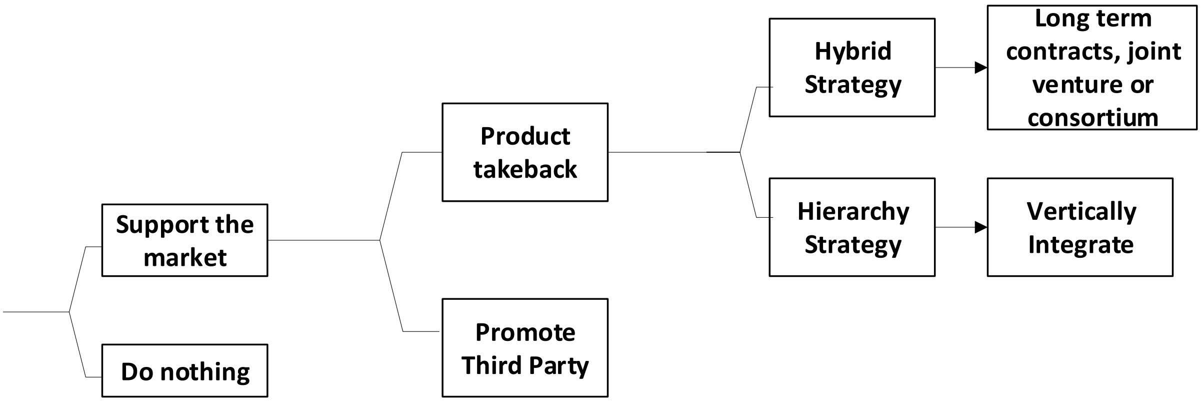


Figure 2.4: Product recovery strategy alternatives (Toffel, 2003)

1. Do nothing

This is usually common in countries where there are no strict regulations and OEMs do not feel obligated to recover their products and they take no notice of where disposed products end up.

2. Promote the market

The OEM only provides support for the recovery program without actually taking part in it. Usually the recovery is carried out by third parties. An example is Apple: they design their products for ease of disassembly and recycling but it is not involved in the recovery of their used products.

3. Long-term contract

The OEM signs a contract or licence that authorises another organisation to perform recovery of its products. An example is Nokia when it authorised ReCellular to be its North American service and remanufacture centre for its mobile phones.

4. Joint venture with a recycler

Toffel (2003) gave an example of HP forming a joint venture with Micro Metallics Corporation, a subsidiary of Noranda. In the venture, HP supplies the warehouse facilities at their Roseville, California facility and Micro Metallics provides the process technologies and staff for the disassembly and recycling operations. While HP sells the recovered components that have value on the secondary market, the recovered fine metals are shipped to Noranda's smelters.

5. Joint ventures with competitors or establish industry consortiums

Several OEMs usually work together to gain economies of scale by designating one company in a region or country to manage the initial stages of the reverse logistics processes to reduce collection costs. Also, manufacturers facing the same problems can develop a cost-effective product recovery system. An example is a consortium for the management of waste electrical and electronic equipment (WEEE) collection in Japan by Sony, Sanyo, Sharp, Hitachi and Mitsubishi.

6. Vertically integrate into product recovery

In supply chain management, vertical integration is usually when an organisation decides to take over some activities involved in its production process. In this case, OEMs will invest in the technology and skills required for the recovery of their products and in this way, the manufacturer gains knowledge about their end-of-life products. This may also assist should the manufacturer consider activities such as design for recovery. Toffel (2003) also gave an example of IBM. IBM owns recovery centres that accept any manufacturer's CPU, monitor and peripherals and then refurbishes, donates or recycles them. IBM also designs their products for upgradability, reusability, recyclability and safe disposal. To achieve economies of scale in transportation, IBM's recovery facilities in Europe collect all types of IBM products to initiate local disassembly and ship only those components valuable for remanufacturing to product-specific factories.

The strategies listed are not mutually exclusive. Some organisations use hybrids of these strategies. The closed-loop is usually defined by OEMs who become involved in the recovery processes of their products, mostly in the joint venture and vertical integration strategies and some of the hybrids. The joint venture and vertical integration strategies are the main focus of this research as they mostly define closed-loop supply chains.

Research studies that applied classic operations research optimisation methods focused on problems related to inventory control issues, reverse logistics networks design, lot sizing and hybrid systems. Inderfurth (1997) addressed a problem of product recovery management where a single product is stocked in order to fulfil a stochastic demand of customers who may return products after usage, thus generating also, stochastic returns. Aspects of product planning were investigated by Van der Laan, Salomon, Dekker, and Van Wassenhove (1999), Golany, Yang, and Yu (2001)(2001) and Ferrer and Whybark (2001), who used material requirements planning (MRP) to facilitate the management of a remanufacturing facility.

Lot-sizing problems for mixed manufacturing and remanufacturing facilities were also developed by Beltran and Krass (2002) and Tang and Teunter (2006). Ketzenberg, Guide, and Souza (2003) considered the problem of designing a mixed assembly-disassembly line for remanufacturing. They studied two configurations, under the assumption that the disassembly sequence is exactly the reverse of the assembly sequence.

Phase 3: Coordinating the reverse supply chain

According to Guide Jr and Van Wassenhove (2009), this "is where the business economics perspective linked up with other approaches in modern operations management research such as the game theory and contracting. Game theory models helped to understand the strategic implications of product recovery. Contracting is of importance in closed-loop supply chains because they typically have an increased number of actors". This is the phase where 3PRLPs were also introduced. The main benefits of this phase were that:

- The outcomes provided a greater understanding of channel design issues, upstream durability decisions as well as the role of trade-ins and the interactions between new and remanufactured products.
- This phase established CLSCs as a full-fledged supply chain sub-field using a business economics approach to product returns.

Phase 4: Closing the loop

The research emphasis was on profitability through system design and recognising the different types of product returns throughout the product life cycle. It was the phase when most OEMs recognised that minimising the cost of returns is not always the right perspective, that products have different time sensitivities and that it is necessary to maximise the value of the product over the entire product life cycle.

In this phase, different business models for reverse logistics were identified and distinctions between open and closed-loop supply chains were made.

The Open-loop Supply Chain

Prahinski and Kocabasoglu (2006) stated that in an open-loop system, products do not return to the original producers but they will be recovered by other parties willing and able to reuse the materials or products. This differentiation was further split by Asif, Bianchi, Rashid, and Nicolescu (2012) when they explained the difference between what they termed "the reverse supply chain" and the "complete open loop". Two conditions were stated for the reverse supply chain:

- The recovered cores do not enter the main stream of the forward supply chain.
- The recovered contents of the original products are used by other firms to manufacture products that serve a different purpose.

In a complete open loop, it was stated that "remanufacturing is performed by a third party and the product is distributed to a different market and they are two different forward supply chains, one for the manufacturer and the other for the remanufacturer".

In a different definition, Geyer and Jackson (2004) stated that a reverse supply chain can be described as open when the supply chain that receives the secondary resources produces goods that are different from the original type. This was in support of the second condition stated by Asif et al.(2012) but it contradicts the description by Prahinski and Kocabasoglu (2006) as a used product can go to a different supply chain and that supply chain can produce a similar product to the original supply chain. This scenario is termed an open loop by Prahinski and Kocabasoglu (2006) but Geyer and Jackson (2004) termed it a closed-loop system.

Closed-loop supply chains

Prahinski and Kocabasoglu (2006) defined closed-loop supply chains as "supply chains designed to consider the processes required for product returns in addition to the traditional forward chain processes". They state that in closed-loop supply chains, the product returns to the OEM and that they can lead to a business making adjustments in product design and procurement practices.

Asif et al. (2012) further explained the concept by listing the three necessary conditions for a supply chain to be described as a closed loop supply chain:

- The core is collected by the OEM or the third-party remanufacturer that acts as the supplier to the OEM.
- The core enters and is used in the mainstream of a manufacturing forward material flow.
- The remanufactured product is sold in the same way as the new one, i.e. the remanufactured product is not considered as a different product variant and order and supply is not handled separately.

Figure 2.5 summarises the concepts explained by Asif et al. (2012).

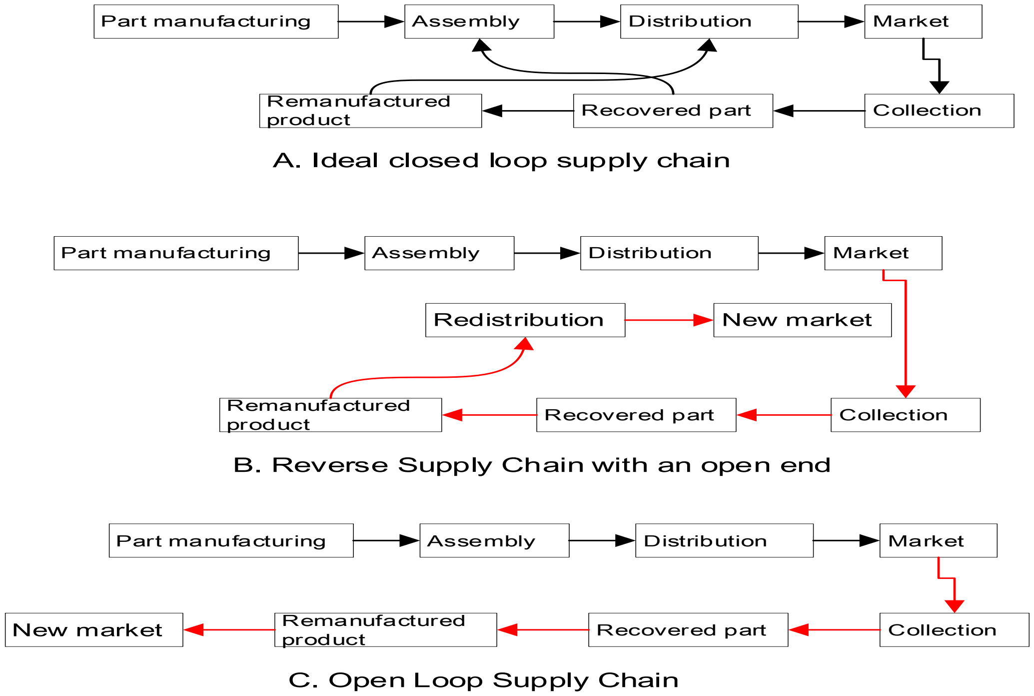


Figure 2.5: Differences between open-loop and closed-loop supply chains (Asif, Bianchi, Rashid & Nicolescu, 2012)

Once again Geyer and Jackson (2004) contradicted Asif et al.(2012) and Prahinski and Kocabasoglu (2006). Asif et al.(2012) and Prahinski and Kocabasoglu (2006) stressed the need for products to return to their OEM in a closed-loop supply chain. Geyer and Jackson (2004) simply define a closed-loop supply chain as "if the supply chain that receives the secondary resources produces goods of the original product type".

In addition to the differentiation by Asif et al. (2012), a typology of closed-loop supply chains was developed by Wells, Seitz, and Seitz (2005). They identified six types of closed-loop supply chains:

1. **Internal closed loop** occurs within the point of manufacture and is confined to the reuse of materials collected as waste from manufacturing. It is micro in character, involves minimal logistics management and it enhances business performance through material efficiency. In this type, a secondary class is where the waste material is degraded to a lesser application.
2. **Post-business** where material is collected and returned between distinct business entities. This type may bring in a third party, to receive recycled material, necessitating separate logistics management, for example steel cut-offs from a pre shop may be sent to a mini mill to be melted down for new steel.
3. **Post-consumer** involves the continuous flow from the point of manufacture, out to consumers and then back to the same point of manufacture. The product remains within a product or industrial sector, so it is closed in this sense.
4. **Post-society** is more expansive and inevitably involves materials recycling rather than forms of remanufacturing. Many products are eventually disposed of and the metal content is recycled via an entirely independent network.

5. **Fully or genuinely closed loop** means that returned and remanufactured products (or parts) are incorporated in the production of new, premium products e.g. photocopying machines.
6. **Modification of closed loop** happens when remanufactured products are classified and sold as 'second class' products on a secondary market, such as re-treaded tyres. The remanufacturing output is not classified as new and is sold on a non-premium market.

This dissertation mostly focused on the closed-loop supply chains as defined by Prahinski and Kocabasoglu (2006) and Asif et al. (2012). In this dissertation, the following conditions had to hold for a supply chain to be defined as a closed-loop:

- If an OEM forms a joint venture with a third-party (3P) remanufacturer, the recycler will have to send the recycled products back to the OEM where they will be stored in the same inventories and follow the same distribution and sales channels.
- An organisation that manufactures, sells and remanufactures and resells its own products.
- An organisation that collects and remanufactures components from its used products for use in the assembly of new products.

Distinguishing between open and closed-loop supply chains paved the way to specific investigation of issues related to closed-loop supply chains. One of these was that of prices and markets for new and remanufactured products. This defined Phase 5 of the evolution of Reverse Logistics.

Phase 5: Prices and markets

The phase approaches the problem of market cannibalisation between new and remanufactured products as well as the issue of valuation of remanufactured products. According to Guide Jr and Van Wassenhove (2009), this phase began to link other disciplines such as marketing and accounting to the operations management perspective.

Ferguson and Toktay (2006) developed models to support a manufacturer's recovery strategy in the face of a competitive threat on the remanufactured product market. Atasu, Guide, and Van Wassenhove (2008) provided an alternative strategy to investigate the profitability of remanufacturing systems under different costs, technology and logistics structures. In their investigation, they included demand-related issues such as green segmentation, OEM competition and product life cycle effects. The cannibalisation effect was addressed by means of auctions by Guide and Jiayi (2010) to determine the consumer's willingness to pay for both new and remanufactured products. Auctions allowed for the better understanding of the potential impact of offering new and remanufactured products at the same time.

Phase 5 is still evolving with the evolution of closed-loop supply chain research.

2.3 The bullwhip effect

Lee, Padmanabhan, and Whang (1997) mentioned an "almost ubiquitous problem" occurring in supply chains. This problem was the so-called bullwhip effect. Dominguez, Cannella, and Framinan (2014) referred to the bullwhip effect as, a "phenomenon by which even small variations in customer demand may generate high alterations in upstream production of suppliers". Studying this phenomenon has become interesting because a lot of costs have been associated with the BWE. Wang and Disney (2016) mentioned the following costs associated with the BWE:

- Setup and shutdown of machines.
- Idling and overtime in the workload.
- Hiring and firing of the workforce.
- Excessive upstream inventory.
- Difficulty in forecasting and scheduling.
- Systems' nervousness.
- Poor supplier or customer relationships.

The study of the BWE has evolved over the years and it is a topic that continues to be of particular interest to both industry and academia. Jia, Wang, and Luo (2011), Holweg and (2011) and Holweg and Disney (2005) documented the study of stability in a supply chain (BWE) from when it originated and listed six stages. In this research, literature on the BWE has been reviewed according to the stage of evolution of the BWE in which it was published.

1. Production and inventory control (before 1958)

This was the period when production and inventory control models were built based on the control theory and the dynamic characteristics of production and inventory control systems were discussed.

Simon (1952) intended to give an introduction to servomechanism theory and its use to production and inventory control problems. Their tentative conclusion was that the basic approach and fundamental techniques of servomechanism theory can be applied to the analysis and design of procedures for controlling the rate of manufacturing activity. In this exploratory phase, Vassian (1955) also discuss the use of discrete variable servo theory to the analysis of inventory control systems with the objective of designing an inventory control scheme that minimised the variance of the inventory balance subject to imposed conditions. They clearly stated the dependence of the inventory level on the sales forecast error and system constants.

A discrete time bullwhip and inventory variance problem for the classical order up to (OUT) policy with MMSE forecasting using z transforms was provided by Magee (1958) in his book. A similar book that formally described the use of z transforms in production and inventory problems was published by Brown (1963).

2. Smoothing production (1958–1969)

Forrester (1961) built original dynamics models of the supply chain using DYNAMO revealing the counterintuitive phenomenon of fluctuations in the supply chain. This approach formed the basis of systems dynamics modelling and a lot of contributions have been made, many of which focus on demand signal amplification in supply chains with more than one echelon. Another academic breakthrough was when Adelson (1966) examined a linear production and stock control scheme in which exponential smoothing was used for forecasting with particular emphasis on noise reduction and transient response. They used z transforms extended to include stock and production to analyse the role of different exponential smoothing rules inside a continuous time production and inventory control system. In addition, Deziel and Eilon (1967) developed a simulation to generate an exact solution to the discrete time bullwhip problem. They recognised the importance of the way in which the production and inventory control system influences the stationary variance of the inventory levels.

At this stage, seasonal fluctuations in inventory and demand amplification were gaining attention, but the terms BWE and stability of supply chains were not formally proposed. The emphasis of research in this period was traditional production management.

3. The development of the control theory (1970–1989)

In the development of the control theory stage, customer demand was assumed to be constant and productivity was random.

Schneeweiss (1975) derived a linear policy for a production smoothing problem with a quadratic criterion. This used a range of techniques to develop an optimal design of production and inventory control, minimising inventory variance. Bertrand (1980) used the classical control theory to design the dynamic behaviour of an actual production and inventory control system for a diffusion department. Attention in this work was paid to the steady state behaviour, the impulse response and the variance amplification of the controlled system. The case presented showed that some serious errors in production and inventory control design can be avoided through analysis and by means of the classical control theory.

Towill (1982) studied the ability of the Inventory and Order-Based Production Control System (IOBPCS) to recover from shock demands and to protect the manufacturing process from random variations in demand. This showed that the feedback path is important in good control and that adequate performance cannot be obtained by the forward flow alone. In this stage, an analysis of the behaviour of production levels and stocks in an integrally controlled multi-product, multiphase production system was carried out by Bertrand (1986) to show that certain variations in the master production schedule lead to large short-term variations in production.

4. Stage of the Beer Game (1989–1997)

This is the stage when systems dynamics became popular as a method of modelling supply chains to study the behavioural effects in supply chains.

Sterman (1989) suggested a general stock management model after doing some experimental studies on the 'Beer Game' of MIT. Naim (1995) discussed the feedback control and stock replenishment using continuous time equations. A lot of articles have emerged as a result of the Beer Distribution Game. An example of this is Larsen, Morecroft, and Thomsen (1999) who developed a model to show how the cascaded structure of a production-distribution chain can produce a wide variety of dynamic behaviours. The analysis illustrated why it is so difficult for decision-makers to 'navigate' low-cost regions.

5. Further development of the BWE (1997–2000)

This stage did not make a thorough study of feedback control. The most common article was by Lee et al. (1997) who claimed that "the Bullwhip effect is a phenomenon where orders to the supplier tend to have larger variance than actual sales to end customer and the distortion propagates upstream". They conducted an exploratory research on the main causes of the BWE and identified four factors: (1) demand signal processing, (2) rationing game, (3) order batching and (4) pricing variations. This article formed the basis of research on the BWE as most research was centred on either some or all of the factors mentioned by Lee et al. (1997).

Matsuyama (1997) examined the inventory levels under a system in which the demand function consists of two parts. Similarly, Graves (1997) considered an adaptive base stock policy for a single item inventory system, where the demand process is non-stationary. They characterised the inventory random variable and used it to find the safety stock requirements. They concluded that the required inventory is dependent on the lead time and it behaves differently for the case of non-stationary demand compared to stationary demand.

As far as quantification of the BWE was concerned, in this stage, Chen, Drezner, Ryan, and Simchi-Levi (2000) quantified the BWE for a simple, two-stage supply chain consisting of a single retailer and a single manufacturer. They included two causes of the BWE mentioned by Lee et al. (1997): demand forecasting and order lead times. Their research demonstrated that the BWE can be reduced but not completely eliminated by centralising demand information in a supply chain.

Raghunathan (2001) showed that in a two-level supply chain with stationary autoregressive (AR) (1) end demand, the manufacturer benefits significantly when the retailer shares point-of-sale demand data. Raghunathan (2001) demonstrated through analytical and simulation methods that the manufacturer's benefit is insignificant when the parameters of the AR (1) process are known to both parties.

A key focus of this stage was investigating relationships and causes of the BWE. Authors like Hosoda and Disney (2004) investigated the relationships between an ordering policy, the variance of inventory levels it maintains and the forecasting scheme that it exploits. They compared the performance of the order-up-to (OUT) policy with a minimum mean square error forecasting mechanism to that of the moving average and the exponentially weighted moving average. The authors also investigated the relationship between the variance of orders and the inventory levels for the three forecasting levels. The authors concluded that OUT policies made up of minimum mean square error (MMSE) forecasting minimise the variance of inventory levels over time. Shortening the lead time will reduce the variance of the inventory levels and the bullwhip produced by the system.

6. Stage of avoiding the BWE (after 2000)

The study of the stability of supply chains has become an independent research field. During this stage, most studies focus on mitigating the BWE.

Another important research in BWE was by Paik and Bagchi (2007) where they tried to identify which of the BWE causes mentioned by Lee et al. (1997) had the most impact. Lead time for the production and distribution of products was listed as one of the causes of the BWE. Disney, Towill, and Van De Velde (2004) concluded that reducing the production and distribution lead time reduces the BWE. This conclusion agreed with that of Sadeghi (2015); Disney and Towill (2003); Kelepouris, Miliotis, and Pramatari (2008), Nagaraja, Thavaneswaran and Appadoo (2015) and Steckel, Gupta, and Banerji (2004). However, Lin, Wong, Jang, Shieh, and Chu (2004) argued that lead time alone would not cause the BWE unless it is coupled with demand forecasting. In the same concept of lead time, Ma and Ma (2017) argued that smaller lead time does not always lower the BWE but much higher lead time does result in higher BWE. In their investigation on hybrid supply chains, Lin, Jiang, Liu, and Wang (2014) concluded that the BWE can be reduced by managers' heuristics of adjusting minimum order processing time to respond to variability in demand. This seemed to agree with Lin et al. (2004). Wang and Disney (2017) also observed that if lead time is stochastic, inventory variance (hence BWE) is dependent upon the average demand level. From all this, two points do exist for lead time and the BWE:

- Long lead times lead to an increase in the BWE.
- The lead time can only impact the BWE in the presence of demand forecasting.

As demand forecasting impacts the effect of lead time on the BWE, it also must have an impact on the BWE. Paik and Bagchi (2007) identified demand forecast updating as one of the three most significant factors that affect BWE in a supply chain. In line with this observation, a variety of comparisons have been carried out using various forecasting techniques to determine which of them resulted in less bullwhip. Li et al. (2014) compared different forecasting methods to the Damped Trend Out System. They claimed that the Naïve, Exponential Smoothing and Holts method of forecasting when used inside the OUT policy will always generate bullwhip for every demand process and for any lead time. This is in contrast to the Damped Trend OUT System which sometimes produces bullwhip and sometimes does not.

Sadeghi (2015) concluded that the BWE for exponential smoothing is less than that of the moving average technique. A different result was obtained by Costantino, Di Gravio, Shaban, and Tronci (2015) who claimed that the moving average achieved lower BWE than the exponential smoothing method. The authors introduced a new method of forecasting called SPC-FS which they claimed to be superior to traditional forecasting methods in terms of BWE. Some authors investigated the impact of the forecast span on the BWE. These authors include Disney and Towill (2003), Disney et al. (2004) and Ma and Ma (2017) and they concluded that increasing the span of the forecast reduced the BWE.

Considering non-linearity in the ordering policy, Wang, Wang, and Ouyang (2015) argued that the magnitude of the BWE will eventually become bounded after growing for the first stages of the supply chain. The customer demand and demand fluctuation frequency would affect this bounded magnitude whilst the supplier's demand forecasting method has no effect at all. Ma and Ma (2017) argued that demand volatility is a complex factor in BWE measurement. Cao, Xiao, and Sun (2017) stated that supply and demand fluctuation cannot eliminate the BWE in any case due to the systematic factors in the supply chain. Assessing the demand variation in the life cycle of a product, Nepal, Murat, and Chinnam (2012) observed that the BWE and net stock amplification rose sharply during the peak phase of a product's life cycle. They also observed that the performance of a system as a whole deteriorated when there was a change in the life cycle demand.

The impact of demand volatility and supply chain structure was looked into by Dominguez, Cannella, and Framinan (2014) where they claimed that the number of entities in a supply chain has no impact on the BWE when the supply chain is facing a stable demand but it does have a direct impact when the demand is unstable. Steckel et al. (2004) argued that the chain design has an effect on bullwhip; the more links in the supply chain, the greater the bullwhip effect. Sirikasemuk and Luong (2017) mentioned that when demand processes are not independent, the correlation coefficient between the two error terms and the variances in the error terms have some influence on the BWE.

It is quite evident that demand forecasting does have an impact on the BWE in a supply chain, though it is still arguable as to which method reduces bullwhip. The continued investigation into forecasting methods and the BWE shows that there is still a lot to be explored in this area which has most of the recent publications over all other areas. From the observed trends, it is quite possible that literature on demand forecasting and the BWE will continue to increase as authors try to define better methods to mitigate the bullwhip effect.

Whenever there is demand forecasting, there definitely is an ordering policy and most research has attributed the OUT policy as a culprit in increasing the BWE. Dejonckheere, Disney, Lambrecht, and Towill (2003) stated that bullwhip is guaranteed in OUT policy irrespective of the forecasting method used. George and Pillai (2016) agreed with this conclusion as they attributed the growth of BWE in serial supply chains to the OUT policy and its variants. Sucky (2009) also agreed with this as they claimed that OUT systems usually result in bullwhip but the strength of the effect depends on the statistical correlation of the regarded demands. Whilst investigating the BWE in retail, Jin, Williams, Waller, and Hofer (2015) discovered that aggregating sales and order data has a masking effect on the BWE. However, they argued that the efficiency of each inventory model depends not only on the external environment but also on the decisions of other levels and even on the position in the supply chain.

In trying to mitigate the BWE due to OUT policies, Disney and Towill (2003) and Disney et al. (2004) argued that the BWE can be reduced by taking a fraction of the error in the inventory pipeline position rather than accounting for errors every time an ordering policy is made. Lin et al. (2014) also claimed that an OUT policy that consists of demand forecasting, WIP adjustment and backlog adjustment is more indicative of bullwhip dampening than the traditional OUT policy. Recent research has tried to introduce more advanced ordering policies for reducing bullwhip, for example Fu, Ionescu, Aghezzaf, and De Keyser (2014) and Fu et al. (2015) introduced Model Predictive Control strategies (MPC) in ordering policies and concluded that MPC based strategies can significantly lower the BWE. They claimed that the decentralised MPC configuration resulted in inferior performance but it still proved to be better than conventional ordering policies. With so much attention and continued research, it is, however, surprising that inventory replenishment policy is not listed among the three most significant factors mentioned by Paik and Bagchi (2007).

The lack of information sharing has been listed by Lee et al. (1997) as one of the causes of the BWE. Dejonckheere, Disney, Lambrecht, and Towill (2004) supported this by claiming that information sharing is beneficial especially for OUT policies since the magnitude of the BWE can be reduced for higher levels of the supply chain. Kelepouris, Miliotis, and Pramatari (2008) identified the need for information sharing in reducing the BWE. Steckel et al. (2004) argued that point of sale information is not necessary; its being beneficial depends on the nature of the demand pattern. In investigating the quality of information on inventory shrinkage, Dai, Li, Yan, and Zhou (2016) claimed that the BWE is magnified along the supply chain when higher quality information on inventory shrinkage is obtained i.e. real time rather than statistical data.

Based on conclusions made by most of the authors, information sharing is essential in reducing the BWE and it is also a factor of interest in bullwhip research.

Lee et al. (1997) included sales promotions as one of the contributors to the BWE. Their conclusions were questioned by Trapero and Pedregal (2016) who designed a novel time metric to measure the BWE in real-time fashion. They concluded that the BWE is not constant over time, it is reduced during the promotional periods and it is bigger before and after the promotion takes place. This was in contrast to Lee et al. (1997) who claimed that the BWE increases during the promotion.

Price changes are also listed as one of the causes of the BWE. Price changes lead to rationing and shortage gaming. Retailers try to buy products before price increases and stock them. This may lead to unwanted inventory especially if the price is to drop again. Ma and Ma (2017) also investigated retail price and market share. They claimed that it is inadvisable to conduct large fluctuations of price. Their conclusions were that the BWE becomes larger when competition becomes fiercer. Ma and Ma (2017) also emphasised the need for retailers to take measures to reduce the influence of competitors' prices. Duan, Yao, and Huo (2015) investigated the impact of price changes from the context of substitute products. The authors claimed that BWE is not affected solely by a product's own factors but also by its substitute factors. They also discovered that an increase in own price changes is associated with a decrease in BWE in direct effect but increases in BWE in terms of overall effect. Increases in the number of price changes of substitute products and own stock-outs can lead to an increase in the BWE. Zotteri (2013) claimed that forward buys and price fluctuations play a decisive role in the BWE after observing an impressive degree of variability in BWE across product families within the same country, same industry and same company.

One observation is that the most recent research on the BWE are unearthing new concepts, some of which contradict the findings of early research on the BWE which makes the topic more open for further research. Paik and Bagchi (2007) listed rationing and shortage gaming as one of the three factors that had the most significant impact on the BWE, yet it is also one topic that has not been looked into much. Goodarzi, Makvandi, Saen, and Sagheb (2017) who looked into this issue most recently, stated that cash flow bullwhip (CFB) stems largely from rationing and shortage gaming in both centralised and decentralized supply chains.

Very little focus has been placed on behavioural causes of the BWE. Most authors tend to focus on operational causes. However, Gupta (2012) mentioned that supply chain managers may not always be completely rational and they confuse forecasts with targets. They identified behavioural causes of the BWE such as misuse of basic stock policies, misperceptions of feedback and time delays, panic ordering reactions after unmet demand and perceived risk of other players. Gupta (2012) also mentioned other causes such as unforecast sales promotions, lack of customer confidence, customers turning back sales orders, freight incentives, overreaction to backlogs, neglecting orders to reduce inventory and delayed information and material flow. Haines, Hough, and Haines (2017) investigated the impact of decision-making on the BWE and concluded that decision-makers that felt that they understood cause and effect relationships were more likely to incorporate additional information to their decision-making process and thereby make better ordering decisions. Costas, Ponte, de la Fuente, Pino, and Puche (2015) even tried to mitigate the BWE using Goldartt's Theory of Constraints. This also added another gap in BWE literature that is worth exploring further.

While most authors focused on the causes and mitigation of the BWE, other authors had their own arguments concerning the presence of bullwhip in a supply chain. Gorman and Kanet (2011) clearly argued that because of the article by Lee et al. (1997), most researchers have been made to believe that the bullwhip effect should always be mitigated. They argued that because of the belief that variability and inefficiency are intertwined, supply chain researchers and practising managers have spent considerable effort attempting to mitigate the bullwhip effect. This was agreed on by Mackelprang and Malhotra (2015) who argue that while the traditional BWE often yielded reduced Return on Assets (ROA), it ultimately has no relationship with a firm's operating margin. Gorman and Kanet (2011) claimed that variance in demand in the supply chain is not always detrimental. The idea of good and bad bullwhip is explained in the paper, citing that bullwhip is bad when increased variance of demand is unexplained, for example when the forecast of demand unwittingly increases. The article mentioned that in most cases the increase in variance is predictable or planned as a result of deliberate economic analysis. In the article, an example of bad bullwhip is a result of the OUT policy where the supplier has to carry more inventories to meet the same service level requirements as a result of the buyer's forecasting technique. An example of good Bullwhip is in the case of lot sizing. The example of Pampers from Procter & Gamble was used to explain the concept of taking advantages of economies of scale for all the players who place orders in the supply chain and even though the variability increases, this was classified as good bullwhip because of fewer shipments and improved fill rates.

Alony and Aneiros (2007) summarised the various causes of the BWE. They classified the causes in the five categories of supply chain structure and processes, material and information lead times, supply variability, other causes and additional causes. Table 2.3 summarises these causes and their sources. In addition, Lee at al. (1997) summarised the impact of the BWE in the supply chain;

- Excessive inventory investment
- Poor customer service
- Misguided capacity plans
- Missed production schedules

Table 2.3 : Summary of causes of BWE

BWE Cause	Explanation	Authors
	Supply Chain Structure and Processes	
Demand forecast updating	Reliance on past demand information for present demand situation.	Lee et al. (1997)
Order batching	Batching of orders to minimize unit ordering cost and production cost. Causes distortion of demand information.	Lee et al. (1997)
Rationing and Shortage gaming	In an environment where there is a shortage, buyers tend to over order to secure resources and suppliers tend to correct this by rationing to smaller quantities.	Lee et al. (1997)
Price variations	Promotions and discounts disrupt regular buying patterns buyers will want to capitalize on the discount offered during a short period of time, while the manufacturer suffers an uneven production schedule, unnecessary inventory costs and distorted demand information.	Lee et al. (1997)
	Material and Information lead times	
Material and information lead times	An order placed by one business unit reaches an upstream supplier after an information lead time and as the product is made, the order is completed and delivered, there is a material lead time. As demand for materials may change from the time the order is placed to the time the material is received, difficulties arise in effective management of a supply chain.	Paik and Bagchi (2007) Towill (1991)
	Supply Variability	
Machine Breakdown	Potential to exaggerate demand due to over ordering in times of breakdowns and shortage is perceived by downstream players in the supply chain.	Paik and Bagchi (2007) Forrester (1958)
	Other Causes	
Capacity limit	Decreases in capacity levels cause excessive swings in the supply chain once production problems are detected down the chain. This causes erratic ordering by downstream members and causes a Bullwhip effect.	Paik and Bagchi(2007) Forrester (1958)
Number of echelons	Removal of one echelon removes the amplification caused by the pipeline and inventory accumulation in that echelon.	Towill (1991) Paik and Bagchi (2007)
	Additional Causes	
Lead time variability	The level of lead time changes and increases does not initiate the BWE but the quality of information does.	Chatfield, Kim, Harrison & Hayya (2004)
Workloads	As higher workloads deteriorate process quality, more rework is required, which in turns results in higher workloads.	Akkermans and Vos (2003)

2.3.1 Current trends and opportunities in the bullwhip effect

From the history of the BWE mentioned at the beginning of section 2.3, it is evident that current research on the BWE in the forward chain is more focused on quantifying and searching for remedies for the BWE. Fransoo and Wouters (2000) argued that although there are many remedies for the BWE summarised in existing literature, the BWE is still a concern in practical supply chains. This is mainly because existing papers analyse BWE in a simple supply chain, consider different business environments and have limited assumptions made regarding practical supply chains which are more complex. This happens because adjusting even one parameter in the system would significantly impact other parameters and influence the supply chain behaviour.

In an invited review, Wang and Disney (2016) explained the evolution of BWE research and what is still being expected in the coming years. In their narrative literature review, the authors identified main topics of interest that are emerging under BWE research and which serve as a reminder that the BWE is still an interesting topic of research. The main topics are briefly described below:

1. Bullwhip in complex systems

There is an argument that supply chains are more complex systems and a representation of supply chains with just cascading echelons is not enough. The decomposition assumption was accused of underestimating bullwhip measures by Chatfield (2013). The consideration of arborescent supply chains by Beamon and Chen (2001) helped to explain that sometimes there is more than one player at each echelon of a supply chain. "Future research on complex systems will investigate other kinds of non-linear mechanisms in more realistic supply chain models such as capacity constraints, lost sales, bargaining, competition and transhipment" (Wang & Disney, 2016).

The concept of complex supply chains was also introduced by Ma, Wang, He, Lu, and Liang (2015) when they presented an argument that the BWE in supply chains cannot be investigated without considering the interactions among supply chains. They investigated parallel supply chains with interacting price-sensitive demand and concluded that mangers who ignore interactions between supply chains are likely to overstate or underestimate the BWE in the supply chain. Ma and Ma (2017) claimed that market competition monotonously impact the BWE but it is a simple factor. These factors were not listed by Lee et al. (1997) but they are factors worth investigating.

2. Bullwhip in service chains

Most research assumes tangible products in a make-to-stock environment where inventories can be stored as a cushion for variations in demand. There is barely consideration for the make-to-order or service supply chains where production and consumption occur simultaneously. For this reason there is a need to develop measures of bullwhip for service supply chains.

Besides the famous articles by Akkermans and Vos (2003)and Akkermans and Vos (2013) where they investigated if the BWE in service supply chains is similar to that in manufacturing, no further effort has been made to investigate this issue further.

3. Bullwhip with price consideration

Wang and Disney (2016) mentioned that "research on the influence of process on the BWE requires models that incorporate price setting and negotiation processes, dramatically increasing the complexity of the model".

4. Bullwhip with resource competition

This is a phenomenon that was investigated by Lee et al. (1997) in the form of rationing and shortage gaming. This occurs when retailers perceive a shortage in a commodity and they buy more than necessary to cover for the period when there is a shortage. However, competition may also arise in the form of retailers competing to sell their products. This has not been addressed in literature.

5. Bullwhip and sustainability

Sustainability issues always encompass social, economic and environmental aspects. Wang and Disney (2016) argued that the social impacts of the BWE are missing in literature. In the same way, literature on the environmental aspects has focused on the BWE in closed-loop supply chains by focusing mainly on remanufacturing and recycling without considering other green issues such as pollution and carbon emission.

6. Bullwhip as an extended concept

Wang and Disney (2016) noted that in its evolution, the BWE has extended from amplification of material flow to a much larger set of phenomena. The bullwhip term has been extended to any kind of trend that is both persistent and repetitive. Bullwhip and bullwhip-like patterns have emerged in the forms of material flow, cash flow, workflow and even regulations. These make it interesting to investigate where the BWE is headed next. For example, Goodarzi et al. (2017) investigated Cash Flow Bullwhip and stated that when information on ordering policies is not shared among supply chain members, parameters at the downstream are more important than parameters in the upstream in reducing Cash Flow Bullwhip.

This dissertation extended the concept of BWE from a sustainability point of view. It mainly focused on reverse logistics and closed-loop supply chains as means of achieving environmental sustainability.

2.3.2 Bullwhip effect quantification and measurement

Most authors on the topic of BWE tried to mathematically model and measure the phenomenon using various methods. Alony and Aneiros (2007) explored the various ways of modelling supply chain dynamics and explained their strengths and weaknesses where measurement of the BWE is concerned. Table 2.4 summarises the findings by Alony and Aneiros (2007). The authors argued that although the BWE has been studied by various modelling techniques, these techniques suffer from a lot of limitations. They claimed that the supply chain models are often simplified to a large degree; the causes are often investigated in isolation and their sources do not always stem from real supply chain systems.

Fransoo and Wouters (2000) investigated the problems in measuring the BWE and concluded the same problems of measuring a supply chain in isolation. They mostly explained the impacts of data aggregation in measuring BWE. They argued that from the same demand data, different bullwhip effects can be calculated depending on the way that demand data is aggregated.

They advised that the main consideration for choosing a particular type of aggregation is the particular problem that is caused by demand fluctuations in a particular supply chain and that bullwhip measurement should give information about the causes of the demand fluctuations. In their paper, Fransoo and Wouters (2000) identify four types of demand data aggregation for a supply chain that has P products and M outlets:

i. **Product/outlet aggregating** is the most detailed analysis, determining the standard deviation for all available series, resulting in P×M standard deviations and bullwhip measurements.
ii. **Product aggregating** happens when demand per product is aggregated over the outlets and this indicates the variability in demand of the product over the entire echelon, not distinguishing between individual outlets. Product aggregation assumes pooling between the outlets and results in P bullwhip measurements.
iii. **Outlet aggregating** involves aggregating over products. This indicates the variability in demand of an outlet, not distinguishing between individual products. The method requires that the product demands be added up, by using some kind of weighing factor and results in M bullwhip measurements.
iv. **Echelon aggregating** means aggregating over the outlets and products and the variability of total demand at the echelon can be determined. Different product demands can be added up using a weighting factor and it results in 1 bullwhip measurement.

This research however, assumed a one product, one outlet serial supply chain, which gave one bullwhip measurement.

Table 2.4: Modelling supply chains

Method	Explanation	Strengths	Weaknesses
Analytical modelling	• Characteristics of a supply chain are derived using mathematical theories such as probability, calculus and linear algebra • Draws a number of assumptions regarding the mathematical robustness of the model	• Computationally efficient • Have been used to understand the behaviour of a model and the effects of information sharing.	• Exact evaluations of supply chains are difficult if the model is driven by stochastic variables and capacity constraints. • Typically, a supply chain is represented as a two echelon structure and this is too simple to be compared to a real supply chain. • Restrictive in an industry setting and are therefore only used to gain simple insight.
Agent based modelling	• An agent is an autonomous and independent computer program that is coordinated with other agents to achieve a system goal.	• Artificial intelligence capabilities such as learning, reasoning and negotiation carry high value in enhancing the intelligence of a supply chain. • Agents play the Beer game more effectively, agents are more able to track demand, eliminate BWE, discover optimal policies and find good policies under complex scenarios.	• Typically concerned with achievement of a system goal e.g. supply chain optimisation.
Simulation modelling	• Enables elaborate description of supply chain realities e.g. the Beer Distribution Game	• Addresses the limitation of stochastic properties in complex supply chains	• When complexities of real world industries are taken into account (e.g. product mix variation) many causes of the BWE are amplified, mixed or cancelled out or even hard to detect in the data.

Whilst Alony and Aneiros (2007) and Fransoo and Wouters (2000) focused mostly on the problems encountered in measuring the BWE, other authors devised equations for quantifying the BWE. El-Beheiry, Wong, and El-Kharbotly (2004) demonstrate the roles, strengths and weaknesses of four known bullwhip measures and introduced a new measure to mask the effect of order batching on demand variability. Four measures associated with the BWE were listed by El-Beheiry et al. (2004):

Standard deviation has the capability to measure the physical variability of the ordered quantities (or demand). The method has the problem that when the (S, s) review policy is adopted, the value of the standard deviation increases as the mean value increases, therefore it may not be a reliable measure for the severity of the BWE.

$$M1 = std(Q) \qquad (2.1)$$

Where Q is the order placed by the echelon.

Coefficient of Variation is aimed at reducing the severity of the increase in standard deviation due to the increase in the mean. This will overcome the drawbacks of using the standard deviation as a measure by dividing its value by the mean order quantity.

$$M2 = \frac{std(Q)}{Q} \qquad (2.2)$$

Variances Ratio values can describe the behaviour of each member in the supply chain. Values greater than 1 indicate that the member is responsible for amplifying the BWE. The variance ratio does not quantify the actual variability in the ordered quantities. It is also a difficult measure to apply in the case of arborescent supply chain structure as demand is usually generated from more than one downstream member. This difficulty, however, can be overcome by aggregating demand of downstream members.

$$M3 = \frac{var(Q)}{var\,(d)} \qquad (2.3)$$

Where d is the demand by the end customer.

Coefficient of Variation Ratio is used to determine whether a particular supply chain member dampens or amplifies the coefficient of variation. In some cases, it may be equal to the variance ratio if variations in the mean demand at different supply chain members are small. However, if the ratio between the demand and the ordered quantities is less than 1, ordered quantities increase as we go upstream, hence demand variance may also increase. This increase in demand variance may lead to incorrect interpretation of a high coefficient of variation ratio.

$$M4 = \frac{\frac{std(Q)}{Q}}{\frac{std(d)}{d}} \qquad (2.4)$$

El-Beheiry et al. (2004) argued that measures do not tell or quantify the causes of BWE. They also introduced another measure to mask order batching. Order batching is defined as “the increase in the mean ordered quantities along the supply chain as we move upstream”. They argued that each member of the supply chain may contribute differently to order batching and they termed their new measure 'Masked Order Batching Bullwhip measure. It is measured by equation 2.5;

$$M5 = \frac{std\ (Q)}{\frac{Q}{d}} \tag{2.5}$$

In addition to the measures mentioned by El-Beheiry et al. (2004), Coppini, Rossignoli, Rossi, and Strozzi (2010) differentiate between 'generated' and 'suffered' BWE and inventory variance ratios for each echelon in the supply chain. In differentiating the two, the authors were interested in calculating how the actor's position in the supply chain influences his responsibility in bullwhip generation (as well as his predisposition to suffer from bullwhip). Coppini et al. (2010) introduced the following ratios;

$$Bullwhip\ generated\ by\ level\ i = \frac{var(order\ placed\ by\ level\ i)}{var(order\ placed\ by\ level\ i-1)} \tag{2.6}$$

Similarly;

$$Bullwhip\ suffered\ by\ each\ supply\ chain\ level = \frac{var(order\ placed\ by\ level\ i)}{var(customer\ order\ rate)} \tag{2.7}$$

In the case of the retailer, the bullwhip generated and the bullwhip suffered are the same and the retailer only suffers the bullwhip that he generates.

A BWE measurement system based on two criterion assessments of 'internal process efficiency' and 'customer service level' was developed by Cannella, Barbosa-Póvoa, Framinan, and Relvas (2013). In developing this measurement, the authors argued that "most of the studies performed quantify the causes of the BWE and the benefit of tools to avoid this phenomenon only in terms of order amplification, without adopting comprehensive and standard performance metric systems". They also argued that there is substantial room for improvement in the assessment of BWE avoidance techniques. The techniques should take into account focus on customer, operational responsiveness and whole supply chain performance. Cannella et al.(2013) developed a performance measurement system shown in Figure 2.6 which distinguishes how each performance metric is used for each level of the supply chain and the criterion of assessment used.

Supply Chain level		Internal process efficiency	Customer satisfaction
	Single echelon	- Order Rate variance ratio - Inventory Variance Ratio - WIP Variance Ratio - Average Inventory	- Backlog node-by-node - Fill Rate node-by-node
		- Zero-Replenishment	
	Whole supply chain	- Bullwhip Slope - Inventory Stability Slope - WIP Variance Slope - Systemic Average Inventory	- Backlog at retailer - Fill Rate at retailer
		- Systemic Zero-Replenishment	
		Criterion Assessment	

Figure 2.6: The bullwhip measurement system: criterion assessment and supply chain level (Cannella et al., 2013)

Cannella et al. (2013) expressed the importance of the order variance ratio as a "metric that provides information on potential unnecessary costs for suppliers, such as lost capacity or opportunity costs for suppliers and overtime working and subcontracting costs". They state that the order rate variance ratio is preferred because of its ability to monitor the scale of the phenomenon. In their paper, Cannella et al. (2013) also differentiated between two methods of measuring the order variance ratio. The first is based on a definition by Miragliotta (2006) where they define the order variance ratio as "the ratio between the demand variance at the downstream and upstream stages" they term this the "node by node method". In the "customer by node method", the variance ratio is computed as "the ratio of the order variance at a generic node to the order variance of the customer". This is almost similar to the definitions by Coppini et al. (2010) but with different names.

Cachon, Randall, and Schmidt (2007) argued that the order rate variance ratio only informs whether the forces to amplify demand are stronger or weaker than the forces to attenuate demand. For this reason Disney and Towill (2002) argued that the order variance ratio only represents half of the bullwhip problems as a replenishment rule also influences the inventory dynamics. Disney and Towill (2002) introduced a measure of system instability called the inventory variance ratio. Cachon, Randall, and Schmidt (2007) argued that the order rate variance ratio only informs whether the forces to amplify demand are stronger or weaker than the forces to attenuate demand. For this reason Disney and Towill (2002) argued that the order variance ratio only represents half of the Bullwhip problems as a replenishment rule also influences the inventory dynamics. Disney and Towill (2002) introduced a measure of system instability called the inventory variance ratio.

$$inventory\ variance\ ratio = \frac{\frac{\sigma_{inv}^2}{\mu_{inv}}}{\frac{\sigma_d^2}{\mu_d}} \qquad (2.8)$$

Where d is the demand, σ_{inv}^2 is the variance of the inventory and μ_{inv} is the steady-state value of the inventory level.

In a similar fashion, Coppini et al. (2010) defined the 'generated' and 'suffered' inventory oscillations analysis;

$$inventory\ oscillations\ generated\ by\ each\ level = \frac{Var(inventory\ of\ level\ i)}{Var(inventory\ of\ level\ i-1)} \qquad (2.9)$$

They state that this analysis cannot be applied to the retailer level since the customer does not have any inventory. Similarly:

$$inventory\ oscillations\ suffered\ by\ each\ level = \frac{Var(inventory\ of\ level\ i)}{Var(inventory\ of\ the\ retailer)} \qquad (2.10)$$

While the order variance ratio has been given much credit of being able to represent the BWE in supply chains, Cannella et al. (2013) argued that "measuring the internal process efficiency at the individual level (single echelon) is insufficient as it only accounts for individual performance of each link in the chain separately". They suggested a network measure to be used as a complementary measure of the variance ratio, termed 'the bullwhip slope' (BWSl).While the order variance ratio has been given much credit of being able to represent the BWE in supply chains, Cannella et al. (2013) argued that "measuring the internal process efficiency at the individual level (single echelon) is insufficient as it only accounts for individual performance of each link in the chain separately". They suggested a network measure to be used as a complementary measure of the variance ratio, termed "the Bullwhip slope".

The BWSl summarises all the ratios obtained for each stage in a single measure, allowing a complete comparison between different supply chain networks at the network level. The procedure for calculating this metric is to perform a linear regression on the variance ratios using the echelon position as the independent variable. A high value of slope means a fast propagation of BWE through the supply chain network while a lower slope means a smooth propagation.

$$BWSl = \frac{k\sum_{i=1}^{k} p_i \emptyset_i - \sum_{i=1}^{k} p_i \sum_{i=1}^{k} \emptyset_i}{k\sum_{i=1}^{k} p_i^2 - \left(\sum_{i=1}^{k} p_i\right)^2} \qquad (2.11)$$

Where k is the total number of echelons, p_i is the position of the ith echelon and Φ_i is the variance ratio at the ith echelon.

Every method used to quantify the bullwhip effect still suffers from problems and limitations. This explains why the topic of the BWE is still one of interest to academia and industry. In this thesis all the measures related to the bullwhip effect proposed by various authors will be measured and comparisons made.

In this research, the variance ratio as defined by El-Beheiry et al.(2004) was used as the metric for measuring the BWE.

2.3.3 The bullwhip effect in a closed-loop supply chain

While there is a lot of research looking into the BWE in the forward chain, the same cannot be said for research on BWE in closed-loop supply chains.

The most common work into this area was by Tang and Naim (2004) and Zhou, Disney, Lalwani, and Wu (2004) who developed a simple dynamic model of a hybrid manufacturing/remanufacturing system to study an infinite horizon, continuous time, Automatic Pipeline Inventory and Order Based Production Control System (APIOBPCS). They studied the impact of remanufacturing lead time and return rate on the BWE in a closed-loop system using control theory. Their most popular conclusion is that an increase in the return rate led to a decrease in the BWE in the supply chain.

Many authors have used different methodologies such as system dynamics and reached the same conclusions. Authors such as Turrisi, Bruccoleri, and Cannella (2013), Zhang and Yuan (2016),Yuan and Zhang (2015), Wan and Li (2012) and Ma et al. (2014) agreed with the conclusion that an increase in the return rate decreased the BWE in a supply chain. Das and Dutta (2013) agreed with the same conclusion but with the condition that when inventory cover time, inventory adjustment time and remanufacturing percentage are kept constant, that is when an increase in the collection of returns will reduce the BWE in a supply chain.

Even though most of the authors who studied the impact of return rate had almost the same conclusions, some came to totally opposite conclusions. Ding and Gan (2009) argued that when remanufacturing is introduced in a supply chain, BWE increases in the closed-loop supply chain and it increases with an increase in product returns. This opposing conclusion was similar to that of Adenso-Díaz et al.(2012)who first identified factors that were significant in impacting the BWE in both the forward and the closed-loop supply chain. Adenso-Díaz (2012) claimed that the return rate can mitigate the BWE for lower returns but increases the BWE for higher returns.

The existence of opposing conclusions in this research topic is a cause for concern. Cannella, Bruccoleri, and Framinan (2016) in their research to analyse the relationships between remanufacturing lead time, return rate, reverse order policy and the number of supply chain tiers, argue that it is difficult to compare results produced by different researchers. Their main argument is that studies differ in terms of assumptions and research methodology. Examples of the differences noted by Cannella, Bruccoleri, and Framinan (2016) include the number of echelons of the supply chain, available information on the return flow, final demand pattern and assumptions regarding the modelling of inventory and order's quantity.

Because of the arguments presented by Cannella, Bruccoleri, and Framinan (2016), it is necessary to list these studies in terms of their assumptions and methodologies to note the differences and why they cannot be compared. Tables 2.5 and 2.6 list studies on the BWE in a closed-loop supply chain.

Table 2.5: Summary of literature on BWE measurement in closed-loop supply chains

	Tang & Naim (2004)	Zhou & Disney (2006)	Zanoni, Ferretti, & Tang (2006)	Adenso-Díaz et al.(2012)	Turrisi, Bruccoleri, & Cannella (2013)	Das & Dutta (2013)
Methodology	Control theory	Control theory	Simulation	Cider game	Difference math equations	Systems Dynamics
Number of echelons	one	one	one	five	one	five
Final demand pattern.	Random stationery	Random stationery	stochastic	variable	Random normal	Random Normal
Remanufacturing replenishment policy	PUSH inventory policy	PUSH policy	PULL policy	Not specified	PUSH	PUSH
Factors under study	•Information transparency •Return yield •Remanufacturing lead time •Consumption lead time	•Rate of product return •Remanufacturing lead time	•Inventory control policies	• Collection percentage • Lead time • Recycler's capacity limitation	• Rate of return • Remanufacturing lead time	• Collection percentage
Modelling assumptions	•Remanufactured products are as good as new •Different levels of information transparency.	•Remanufactured products are as good as new •Only a fraction of products is returned	• Remanufactured products are as good as new. • Lead times, demand and return processes are stochastic.	No assumptions specified	• Remanufactured products are as good as new • Only a fraction of products is returned.	• Remanufactured products are as good as new products.
Conclusions	• Increasing consumption time increase the BWE. • Uncertainties in yield rate and consumption lead time do not have a significant detrimental impact on system behaviour. • For long lead times, the greater the degree of information transparency, the more susceptible the system is to increased variance.	• Larger return rates lead to less Bullwhip. • Longer remanufacturing lead times have less impact of reducing Bullwhip than shorter lead times.	• Manufacturing Bullwhip can be reduced by using the DUAL policy whilst remanufacturing Bullwhip can be reduced by the shifted PULL policy.	• The time that the customer has before returning the product and the capacity limit of the recycler are insignificant. • Reduced levels of returns mitigate the Bullwhip Effect and high returns increase it.	• When the reverse flow increases, the order variance decreases. • Inventory variance amplification can considerably be reduced only if lead times reach low values.	• The BWE decreases with an increase in collection percentage.

Table 2.6: Summary of literature on BWE measurement in closed-loop supply chains (cont...)

	Corum, Vayvay & Bayraktar (2014)	**Ma & Chai (2014)**	**Cannella, Bruccoleri, & Framinan (2016)**	**He, Yuan, & Zhang (2016)**	**Zhou, Naim, & Disney (2017)**	**Sy (2017)**
Methodology	Simulation	Systems Dynamics	Difference math equation	Systems Dynamics	Control theory	Systems Dynamics
Number of echelons	one	two	variable	three	three	three
Final demand pattern	variable	Random normal	stationery	Random uniform	Random normal	Random Normal
Remanufacturing replenishment policy	PUSH and PULL	PUSH policy	PUSH policy	PUSH policy	PUSH policy	PUSH
Factors under study	• Stochastic demand and return rates • Stochastic manufacturing and remanufacturing lead times • Inventory holding rates	• Recovery rate	• Return rate • Remanufacturing lead time • Number of echelons • Order policies	• Recycling ratio • Recycling delay	• Return yield • Remanufacturing lead time • Consumption lead time	• Impact of different recovery options depending on the level of processing undergone by product returns.
Modelling assumptions	•Remanufactured products are as good as new. •Continuous review policy in forward chain	• Remanufactured products are as good as new. • Product life cycle, supplier production capacity and remanufacturing capacity are limited.	• Production–distribution capacity is unconstrained. • No backlogging allowed	• Manufacturer's capacity, remanufacturer's capacity, electronic product retailer's sales ability, and recycler's recovery ability have no limit	• Shared information but limited to within echelon. • Remanufactured products are as good as new. • Lead times in the forward chain at each echelon are the same.	• Remanufactured products are as good as new products.
Conclusions	• Order variances increase when the percentage of serviceable items from remanufacturing increase. • Hybrid production systems have lower variances than the traditional system.	• High recovery rates reduce the Bullwhip Effect.	• Increasing collection percentage improves supply chain performance. • Increasing the remanufacturing lead time degenerates supply chain dynamics.	• The greater the 3P's recycling ratio, the better the Bullwhip Effect. • With the recycling delay increasing, the Bullwhip Effect can be strengthened in the forward chain.	• Horizontally, higher return yield reduces BWE. • Shorter lead times generally but not always lead to less BWE. • BWE does not always increase from one echelon to the other but may decrease.	• Each combination of recovery options affects the system in varying degrees, with other recovery options having a more significant effect than others and this applied to remanufacturing and refurbishing.

He et al. (2016) investigated the impact of the 3P recycler behaviour on the whole supply chain members and how the environmental policy index impacted the third party recycler behaviour. They investigated factors such as the recycling ratio and the recycling delay. The authors concluded that with recycling delay increasing, the BWE is strengthened in the forward chain and that an increase in the recycling ratio decreases the BWE. Similarly, Hosoda, Altekin, and Sahin (2015) investigated the impact of an advance notice on returns. However, their results were different from those of Tang and Naim (2004) in that they concluded that longer remanufacturing lead times may reduce inventory variance and increasing return yields could have a negative impact on the system. They note a fundamental trade-off between the volume of returns and dynamic supply chain performance.

Table 2.6 showed a different piece of research by Sy (2017) which investigated the impact of different recovery options depending on the level of processing undergone by product returns. Sy (2017) argued that the amplifications increase when remanufacturing is introduced in the supply chain. This research also identified remanufacturing and refurbishing as having more significant impact on the forward chain than other recovery options.

A recent article by Dominguez, Ponte, Cannella, and Framinan (2019) investigated the impact of manufacturing and remanufacturing capacity limits on supply chain dynamics in a closed-loop system. The authors used a difference math equation approach to investigate the impact of combinations of four factors: variability or return yield; variability of customer demand; manufacturing and remanufacturing capacity limits on the BWE in a closed-loop system. They assumed a one echelon supply chain. The authors reached a conclusion that the capacity limitation in the manufacturing line of a closed-loop supply chain limits the BWE suffered by the manufacturer. They also concluded that the capacity limit of the remanufacturing line limits the BWE suffered by the remanufacturer, for cases when the return yield and/or the customer demand have high uncertainties. The capacity limits of the remanufacturer may also reduce the BWE suffered by the remanufacturer.

Despite the differences in modelling assumptions and methodology, three factors have emerged (among the majority of studies) as having an impact on the BWE in the closed-loop supply chain. These factors are the (1) remanufacturing lead time, (2) collection rate and (3) the remanufacturing rate. Whilst the findings of various authors on the topic differ, the majority of the authors agree that increases in the collection rate and remanufacturing rate reduce the BWE in closed loop systems whilst longer lead times result in higher BWE.

In a similar way, the following modelling assumptions have also emerged as being popular among most of the studies;

1. Unlimited remanufacturing capacity.
2. Remanufacturing products being similar to new products and being sold in the same market
3. PUSH inventory control policy for returned products.
4. A one product serial supply chain whereby each echelon is preceded by one entity and also succeeded by one entity.
5. In the forward chain, a common assumption was random stationery demand where the order placed by each echelon is the average forecast plus a fraction of the discrepancy

between actual and target inventory levels and a fraction of actual and target work in process levels as described by Tang and Naim (2004). Most studies have also assumed an exponential smoothing forecast for each echelon.

Whilst the other four assumptions are straightforward, the third assumption needs to be explained. The concept of PUSH and PULL inventory policies for product returns was explained by Van der Laan, Salomon, Dekker, and Van Wassenhove (1999). The authors explain that under the PUSH strategy, remanufacturing is totally driven by the collected items and as soon as there are enough returned products in the recoverable stock (the remanufacturing batch size), they are pushed into the remanufacturing process. Tang and Naim (2004) in their study expanded on the PUSH strategy by assuming that there is no control at the recoverable stock site. As long as there are enough recoverable items, they are pushed into the remanufacturing process. The inventory control is only applied at the serviceable (manufactured items) stock site.

In a PULL strategy however, Van der Laan et al. (1999) mentioned that the timing of remanufacturing operations is not based only on product returns, but on a composite of product returns, future expected demands and inventory positions. Remanufacturing starts as soon as the serviceable stock inventory level drops to a reorder point and there is enough stock of remanufactured items to be sent for remanufacturing.

2.3.4 Capacity limits and the bullwhip effect in a supply chain

Chittamvanich (2007) referred to capacity as, "the processing abilities and limitations that stem from the scarcity of various processing resources". The author further emphasises that capacity can be interpreted as some upper bound on processing quantities. In addition, Murray (2018) differentiated between two types of capacities: the theoretical capacity and the rated capacity. Theoretical capacity is defined as "the maximum output capacity that does not allow for any downtime". Rated capacity is similarly defined as "the output capacity can be used for calculation purposes as it is based on a long-term analysis of the actual capacity". Dominguez et al. (2019) further emphasised that "capacity constraints usually refer to considering upper limits in the order sizes placed by suppliers, or upper limits in the orders' acceptance level"."

Evans and Naim (1994) implemented production capacity constraints in the form of the maximum order rate that can be placed by production facilities. In their investigation, the authors conclude that demand amplification in the forward chain is significantly reduced in systems with constrained capacity. The same conclusion was also reached by Cannella, Ciancimino, and Marquez (2008). The authors argue that an increase in production capacity does not necessarily imply an improvement in customer service. In their investigation, the same authors conclude that the capacity constraint limits the overestimated forecast as it dampens order quantities, hence improving system performance in terms of demand amplification and supply chain stability. Chen and Lee (2012) also concluded that in the absence of order batching, imposing infinite capacity has a smoothing effect on the order variability.

Spiegler and Naim (2014) used systems dynamics to investigate the impact of introducing transport capacity limits on supply chain dynamics. The authors also concluded that introducing transport capacity reduces the BWE. Ponte, Wang, de la Fuente, and Disney (2017) stated that capacity constraints help reduce the BWE as they have a smoothing effect on the orders. They argued that capacity limits act as a production smoothing mechanism at the expense of increasing inventory variability as they can prevent unnecessarily large orders being issued, thereby mitigating the BWE.

However, certain authors did not agree with this conclusion. For example, de Souza, Zice, and Chaoyang (2000) argued that when there is a capacity shortage, material arrival sometimes cannot be processed immediately and parts inventories build up. Increasing capacity decreases dynamics. The authors also argued that temporal capacity expansion policies such as overtime are beneficial. Similarly, Cannella, Dominguez, Ponte, and Framinan (2018) argued that as the producer's capacity increases, supply chain performance increases and capacity does not act like a BWE damper. The authors who considered system responsiveness in their investigation, argue that the negative impact of the low capacity on the BWE is exacerbated by a low responsiveness factor. They suggest that a system with low responsiveness needs a high capacity to limit the saturation.

A totally different conclusion was also reached by Nepal, Murat, and Chinnam (2012). The authors argued that there is no significant evidence to establish the impact of capacity constraints on the BWE. Their conclusion is that restriction in production capacity does not impact the BWE but it significantly increases the net stock amplification. production capacity does not impact the BWE but it increases the net stock amplification significantly.

Literature investigating the impact of capacity limits on the BWE in the forward chain only contradict. Although the majority of the researchers argue that capacity constraints reduce the BWE, there is not much literature to reach a conclusion and it may seem that some assumptions were not explored. For example, most authors model a single echelon supply chain and assume a serial supply chain. They do not look at other supply chain structures and they do not consider multi-echelon supply chains. This shows that capacitated supply chains and the BWE is also a topic that still requires further investigation.

2.3.5 Capacity limits and capacity management in closed-loop systems with remanufacturing

Capacity constraints in a supply chain, have always been looked into from the perspective of the production capacity. In the case of a manufacturing/remanufacturing system, most authors have always assumed an unlimited capacity. However, authors such as Wang, Li, Yan, and Zhu (2016) argued that considering capacity constraint made their paper more realistic and complex. In their paper, the authors investigated optimal production and pricing strategies faced by a manufacturing/remanufacturing system where returns were collected under a name-your-own-price bidding system and the manufacturer had limited capacity to produce both new and remanufactured products.

Aksoy and Gupta (2001) identified two different types of uncertainties that affect the reverse logistics process;

I. **Internal uncertainty** comprises of variations within the remanufacturing process such as the quality level of the product, the remanufacturing lead time, the yield rate of the process and the possibility of system failure.
II. **External uncertainty** comprises of the variations originating from factors outside of the remanufacturing process which include the timing, quantity and quality of returned

products, the timing and the level of demand and the procurement lead times for new parts/products.

The authors claimed that these uncertainties result in the undersupply or obsolescence of inventory, improper remanufacturing plan and loss of competitive edge in the market. In their research the authors considered capacity constraints in the remanufacturing process and they examined the trade-offs between increasing the number of capacity buffers and increasing the capacity at the remanufacturing stations under numerous circumstances. They investigated performance measures such as total cost, average WIP inventory throughput and average remanufacturing time when the remanufacturing stations are operating in uncertain environments.

Uncertainties in the remanufacturing process were further explained by Heydari, Govindan, and Sadeghi (2018). They explained that uncertainties in remanufacturing may occur in the volume or quantity of returned items, their recovery rate and the remanufacturing capacity or yield. They further explained that uncertainties regarding the quality of returned items as well as required processing times of these returns affect the available capacity in the remanufacturing system and results in some degree of capacity uncertainty. In their research, the authors investigated a reverse supply chain model under the uncertainty of remanufacturing capacity. They defined two scenarios:

I. When there is a limited capacity for the remanufacturing of products. In this case too many returned products may cause inefficiency of the reverse logistics system. In their case, excess products that exceeded the remanufacturing capacity were sold as scrap.
II. When there is sufficient capacity, and insufficient supply of returned products. This causes downtime in the remanufacturing capacity and that downtime causes inefficiency in the reverse operations.

Heydari, Govindan, and Sadeghi (2018) aimed at providing an analytical solution for reverse supply chain coordination to maximise supply chain profits where remanufacturing capacity was considered to be a stochastic variable. They argued that stochastic remanufacturing capacity aligned their model more closely to real-world cases. This was the same argument presented by Wang et al. (2016).In their results, Heydari, Govindan, and Sadeghi (2018) revealed that uncertainties in the remanufacturing capacity cause significant changes in the modelling process and also in the output of the reverse logistics system. This was supported by Feng, Zhang, and Tang (2013) who argued that "capacity constraints due to the limitation of resources and the bearing capacity of equipment may play an important role in decision making".

Most of the authors who investigated the concept of remanufacturing capacity considered a case where production in the forward chain shared capacity with remanufacturing in the reverse chain. Poles and Cheong (2011) explained that the efficiency of a production and inventory system for remanufacturing can be affected by a limited system capacity that has to be shared between the remanufacturing and production activities. In their studies, Poles (2013) considered a problem with joint capacity usage for the integrated remanufacturing and production activities and considered factors such as inventory coverage, total system capacity, remanufacturing and production lead times. The research aimed to investigate how the physical flow, information flows and company policies interacted to generate dynamics of the remanufacturing process.

They concluded that the total system costs increase more rapidly if higher capacity is allocated to the remanufacturing than to the production activity. The same author adopted a policy whereby recoverable inventory was stored only when it is required and only the necessary products are inspected and accepted to be stored as remanufacturable items.

In a similar way, Feng et al.(2013) developed a recovery system for perishable items considering production and remanufacturing capacity constraints with the objective of minimising total costs. Georgiadis and Athanasiou (2013) dealt with the long-term demand driven capacity planning policies in the reverse channel based on closed-loop supply chains with remanufacturing under high capacity acquisition cost and increased uncertainty in the operational environment. They mentioned factors that affect capacity planning in a remanufacturing system such as; unknown demand patterns, variability in the product's residence time, dependency of the volume and timing of end-of-use product returns on the demand and sale patterns and uncertainty in the volume and timing of the remanufacturable part of the product returns. They argued that these factors lead to a high risk of shortages in end-of-use product returns since supply may vary and the dismantling volume may turn out to be lower than expected. This will lead to the overcapacity phenomena in collection and remanufacturing capacity. Lieckens (2009) argued that overcapacity may lead to reductions in lead times and inventory costs in a highly utilised and congested reverse logistics network. Vlachos, Georgiadis, and Iakovou (2007) studied the long-term behaviour of reverse supply chains to propose collection and remanufacturing capacity expansion policies while considering factors such as costs, profits and flows.

Other authors considered situations where the remanufacturing capacity and the manufacturing capacity are different and remanufacturing and manufacturing do not share capacities. Such authors include Gong and Chao (2013) and Heydari, Govindan, and Sadeghi (2018). Gong and Chao (2013) studied a capacitated periodic review manufacturing/remanufacturing inventory system with random demand for serviceable products. The firm had constraints in manufacturing, remanufacturing and/or total manufacturing/remanufacturing capacities. In their model, as opposed to Heydari, Govindan, and Sadeghi (2018), the remaining returned products above the remanufacturing capacity were carried over to the next period.

All the above-mentioned literature consider capacity constraints from the perspective of performance measurement but not from the perspective of the BWE in the closed-loop supply chain.

This dissertation extended the gap of capacity constraints in a manufacturing/remanufacturing system by looking at their impact on the BWE in a closed-loop supply chain.

2.4 Research gap

After having mentioned the modelling assumptions made by previous studies, it is necessary to explain the gap that this dissertation addressed. Table 2.7 summarises literature on capacity constraints and the BWE. The table also places the current research and the research gaps that this dissertation addresses.

This dissertation considered the assumption made by most studies that there is no limit to remanufacturing capacity. Only two publications considered capacity constraints in closed-loop systems and their impact on the BWE. The first was by Adenso-Díaz et al.(2012), who dismissed the remanufacturing capacity limits as being insignificant as far as the BWE in closed-loop supply chains was concerned. Dominguez et al.(2019) considered both manufacturing and remanufacturing capacity limits in a supply chain with a single echelon. The authors concluded that the capacity restriction in the remanufacturing line in a closed-loop system limits the BWE suffered by the remanufacturer especially when the return yield and/or customer demand present a high uncertainty. Their other finding is that the capacity constraint of the remanufacturing line may enable the reduction of BWE suffered by the manufacturer.

This dissertation, however, seeks to argue the conclusion by Adenso-Díaz et al.(2012). This is because, although Adenso-Díaz et al.(2012) did consider the recycler's capacity limit, they did not consider capacity limits in other reverse logistics operations such as collection. In this dissertation all these capacity limits will be modelled in a systems dynamics model. It is important to consider these limits in a closed-loop system as well, as this makes mathematical models, "more realistic" as mentioned by Wang et al.(2016). Based on the scenarios described by Heydari, Govindan, and Sadeghi (2018), this dissertation aims to investigate the impact of capacity downtime and inefficiencies in the closed-loop system on the BWE. This makes it different from Dominguez et al. (2019).

In this research, collection and remanufacturing capacity limits are explored based on scenarios where the collected products may either be too much for the available capacity (resulting in inefficiencies and backlogs) or too little (resulting in downtime of the remanufacturing line. Dominguez et al. (2019) did not look into these scenarios, they only imposed capacity limits in both the production and remanufacturing lines. This research also considers a scenario whereby the collector has limited collection capacity such that the available used products can be more than the available collection capacity. Dominguez et al. (2019) did not consider collection capacity limits. Unlike Dominguez et al. (2019), this dissertation did not look into a one echelon supply chain. It considers three echelons, the distributor, the wholesaler and the retailer. The dissertation also uses data from two case studies with different products. Dominguez et al. (2019) and Adenso-Díaz et al.(2012) did not use case studies in their research.

A capacity limit may lead to the concept of the economic batch quantity as explained by Hussain and Drake (2011). The authors explain the concept of the economic batch quantity where it is economically beneficial for a company to produce large batches to reduce the number of facility setups and improve manufacturing efficiency. Such concepts can also be applied to remanufacturing where in this case batching will be as a result of capacity. Van der Laan et al.(1999) also explained the concept of the remanufacturing batch quantity when they explained how remanufacturing begins when enough products have been collected. When the capacity is limited with respect to the collected products, the limit might cause delays in the supply chain which might negatively impact the BWE in the supply chain (based on the conclusion by Zhou and Disney (2006) that longer remanufacturing lead times have less impact at reducing the BWE than shorter lead times).

Table 2.7: Research gap on capacity constraint and the BWE in a closed-loop system

Authors	Type of constraints	Forward chain?	Reverse chain?	Collection capacity?	Remanufacturing capacity?	Remanufacturing backlogs?	Remanufacturing downtime?	Conclusions
Evans & Naim (1994)	Maximum order rate placed by production	Yes	No	No	No	No	No	Capacity constraints reduce demand amplification.
Cannella et al. (2008)	Production capacity	Yes	No	No	No	No	No	Capacity constraints reduce demand amplification.
Chen & Lee (2012)	Production capacity	Yes	No	No	No	No	No	Capacity constraints have a smoothing effect on order variability.
Spiegler & Naim (2014)	Transport capacity	Yes	No	No	No	No	No	Introducing transport capacity constraints reduces the BWE.
de Souza et al. (2000)	Production capacity	Yes	No	No	No	No	No	Reducing capacity increases the BWE.
Cannella et al. (2018)	Production capacity	Yes	No	No	No	No	No	Low capacity increases the BWE especially with a low responsiveness factor.
Nepal et al.(2012)	Production capacity	Yes	No	No	No	No	No	Capacity constraints have no impact on the BWE.
Adenso-Díaz et al.(2012)	Recycling capacity	Yes	Yes	No	No	No	No	Recycler's capacity constraint has no impact on the BWE.
Dominguez et al. (2019)	Production capacity Remanufacturing capacity	Yes	Yes	No	Yes	No	No	Production capacity constraints and remanufacturing capacity constraints reduce the BWE.

This dissertation assumes that remanufacturing and production do not share the same plants although both have limited capacity. Unlike the research by Heydari, Govindan, and Sadeghi (2018) in a situation where product returns are more than the available capacity, the product returns are not sold but they are carried forward to the next period. Whilst authors such as Vlachos, Georgiadis, and Iakovou (2007) focused on capacity expansion policies, this dissertation assumes that capacity is fixed and no capacity expansion policies such as subcontracting are allowed in a case where returned products are more than the available capacity in a given period.

This dissertation also considers introducing capacity limits in a PUSH inventory policy. Remanufacturing and collection capacity limit resulted in remanufacturing being performed in batches defined by the capacity because:

i. The collected products may have been more than the available capacity (number of products that can be remanufactured per unit time) resulting in their being stocked to be remanufactured in the next periods.
ii. The collected products may have been less than the remanufacturing capacity and this resulted in remanufacturing downtime in that period for plants that were very economical and following an efficient strategy.
iii. The collected products may have been equal to the remanufacturing capacity and remanufacturing took place but the BWE will still be impacted by the remanufacturing lead time.

The first and second scenarios, although described by Heydari, Govindan, and Jafari (2017), were explained in more detail by Wei, Tang, and Sundin (2015). In their literature review on core acquisition management, the authors mention the consequences of having a shortage of products for remanufacturing as well as of having too many products returned for remanufacturing. One of the consequences for having insufficient returns as mentioned in the article, is that companies use new products to meet demand. This is one of the scenarios mentioned in this dissertation. This scenario will be modelled as a downtime in the remanufacturing plant. During this downtime, the company will only sell new products. Similarly, Wei, Tang, and Sundin (2015) mentioned the consequences of collecting more than enough. One of these consequences is increasing the holding costs of inventory because the company will have to stock the extra returns. Although this dissertation did not look into costs associated with remanufacturing, the overstocking of returns has also been considered and the extra returns will be modelled as remanufacturing backlogs.

This dissertation models real case scenarios by investigating the impact of the overstocking and understocking of product returns on the BWE in a closed-loop system. These scenarios are modelled through the introduction of collection and remanufacturing capacity limits.

The third scenario listed above is what has been modelled by the majority of the studies when they assumed unlimited capacity, meaning that all collected products were remanufactured. In this study, it was assumed that capacity could not be expanded by means of subcontracting, or reduced, and that the firm could not commence remanufacturing until they have collected enough products. This meant that if the collected products were less than the capacity of the plant, then remanufacturing could not take place for an efficient strategy. Also, in this study, it was assumed that all products were collected from the market and the collection percentage was not a factor under investigation.

The other assumptions in this model are explained in the simulation modelling in Chapter 5.

2.5 Conclusion

This chapter presented the review of existing literature relating to the research issues. The chapter explained the developments in the concept of Supply Chain Management and the introduction of Reverse Logistics and Closed-Loop Supply Chains as a way of protecting the environment and sustainability. In introducing the concept of Closed-Loop Supply Chains, the chapter discovered ways in which activities of reverse logistics are carried out and some problems associated with the process. Some of these included the uncertainty in the quality and quantity of product returns and capacity constraints. The issue of remanufacturing capacity limits was explored and it was discovered that most of the literature on the BWE in closed-loop supply chains assumes no capacity constraints which is not so in the real case scenarios. In the next chapter, the dissertation will explain the various ways of modelling closed-loop supply chains and justify the methodology selected in this research.

CHAPTER 3
REVIEW OF RESEARCH METHODOLOGY

A number of ways can be identified for modelling closed-loop supply chains as well as for obtaining and analysing data. This chapter focuses on these different methodologies, mentioning their strengthsstrength and weaknesses. The chapter explains why in this research the author decided to use mathematical modelling, simulation and case study research methodologies based on the nature of the questions asked and the problem under study. In terms of modelling closed-loop supply chains, methods such as analytical modelling and simulation are explained in detail. Methodologies such as case study, experimentation and surveys are also explained as a way of justifying the choices made by the researcher.

3.1 Modelling supply chains

Borshchev and Filippov (2004) defined modelling as a way of solving problems that occur in the real world that is usually applied when prototyping or experimenting with the real system is expensive or impossible. They claim that modelling allows system optimisation prior to implementation. The main issues of modelling supply chains as stated by Riddalls, Bennett, and Tipi (2000) are that supply chains do not exist in isolation but form part of a network of supply chains satisfying different demands. The linear flow of goods in the supply chain is rare. This means that modelling certain parts of a supply chain may not be 100 percent accurate but may give an insight into the dynamics of supply chains since most supply chains are not located in one place but are distributed globally.

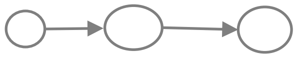
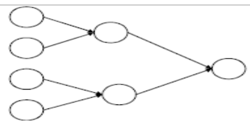
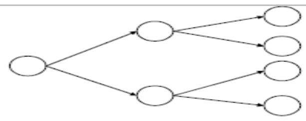
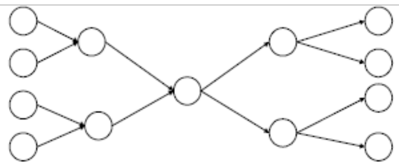
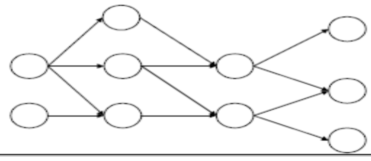
Beamon and Chen (2001) listed examples of supply chain structures for modelling. Table 3.1 lists the supply chain structures and their description. However, most authors have simplified supply chain modelling by assuming serial supply chains. The serial network does not represent any real case studies as supply chains are never stand-alonestandalone entities. It is more of a network used to simplify the modelling of supply chains. According to Beamon and Chen (2001), the number of facilities, the number of echelons and the structure of the material and information flows contribute to the complexity of the supply chain.

In defining the taxonomies of supply chain modelling, Borshchev and Filippov (2004) defined two types of models;

I. Analytic (static) models where the result functionally depends on the input which may be a number of parameters. These models can be implemented in spreadsheets but their main problem is that they do not exist in the real world.

II. Dynamic (simulation) models which may be considered to be "a set of rules e.g. equations and flowcharts that define how the system is being modelled will change in the future, given its present state". Simulation is the process of model execution that takes the model through state changes over time.

Table 3.1: Types of supply chain networks for modelling (Beamon & Chen, 2001)

Network type	Description	Schematic representation
Serial	• Each node in the supply chain has at most one predecessor and one successor.	
Convergent (Assembly)	• Each node in the chain has at most one successor but may have any number of predecessors.	
Divergent (Arborescent)	• Each node has at most one predecessor but any number of successors.	
Conjoined	• Combination of convergent and divergent structure where each comprising sub structure is combined in sequence to form a single, connected structure.	
General	• Neither strictly convergent, divergent nor conjoined.	

In support of this, Tarokh and Golkar (2006) separated analytic and static methods and then compared static models to dynamic models. They stated that "analytical models often employ mathematical programming techniques, which maximize certain benefits by optimizing the strategic design and/or operational policies of a supply chain". The main limitations stated for analytical models are that they are often too simplistic to be of practical use for complex supply chains. Table 3.2 summarises the distinction between static and dynamic models by Tarokh and Golkar (2006).

Given the nature of the problem of this research, it is best to select a dynamic modelling approach. This research seeks to predict the outcomes of changing certain parameters through an iterative process in an environment where time will be changing. A dynamic approach catered for all the needs of this research.

Dynamic modelling approaches have been called simulation by Borshchev and Filipov (2004). In addition to mentioning the benefits of supply chain management, Chang and Makatsoris (2002) listed the benefits of using simulation in modelling supply chains;

- Simulation helps to understand the overall supply chain processes and characteristics by graphics/ animation.
- It is able to capture supply chain dynamics. Using probability distributions, the user can model unexpected events in certain areas and understand the impact of these events on the supply chain.

It could dramatically minimise the risk of changes in the planning process by 'what-if' if analysis. The user can therefore test various alternatives before changing the plan.

There are six types of simulation currently mentioned in the literature. Table 3.3 lists the three less common types of simulation. These three types of simulation cannot be selected for the type of problem being considered in the research. Firstly, spreadsheet simulation cannot handle the complexity and dynamics of a closed-loop supply chain. Dynamic systems are mostly embedded in design and cannot adapt to the minds of modellers, making it less suitable. Whilst a business game like the cider game may be attractive for modelling a closed-loop supply chain as it was applied by Adenso-Díaz et al.(2012), in this research it is impossible to use the cider game because it can only represent one stage (echelon) of a closed-loop supply chain. This research focuses on third parties and the various activities they perform in either a reuse, remanufacture or recycling closed-loop supply chain. The cider game can only support one disposition strategy at a time.

Table 3.2: Differences between static and dynamic models (Tarokh & Golkar, 2006)

Static Models	Dynamic Models
• Describe a system mathematically in terms of equations. • The potential effect of each alternative of each effect is ascertained by a single computation of the equation. • The variables used in the computation are averages and the performance of the system is determined by summing individual effects. • They ignore time based variances. • They do not take into account the synergistic interactions of the components of a system.	• Constantly re-computes its equations as time changes. • It is iterative • It is a software representation of the dynamic or time based behaviour of the system. • Can predict the outcomes of possible courses of action. • Can account for the effects of randomness and variances.

More advanced simulation techniques include Discrete Events Simulation, System Dynamics and Agent Based Modelling. These three types of simulation differ in their representation, aggregation and construction.

In distinguishing the different purposes of the three types of simulation, Tako and Robinson (2012) separated supply chain issues worth modelling into strategic and operational issues and intermediates. Figure 3.1 shows this classification.

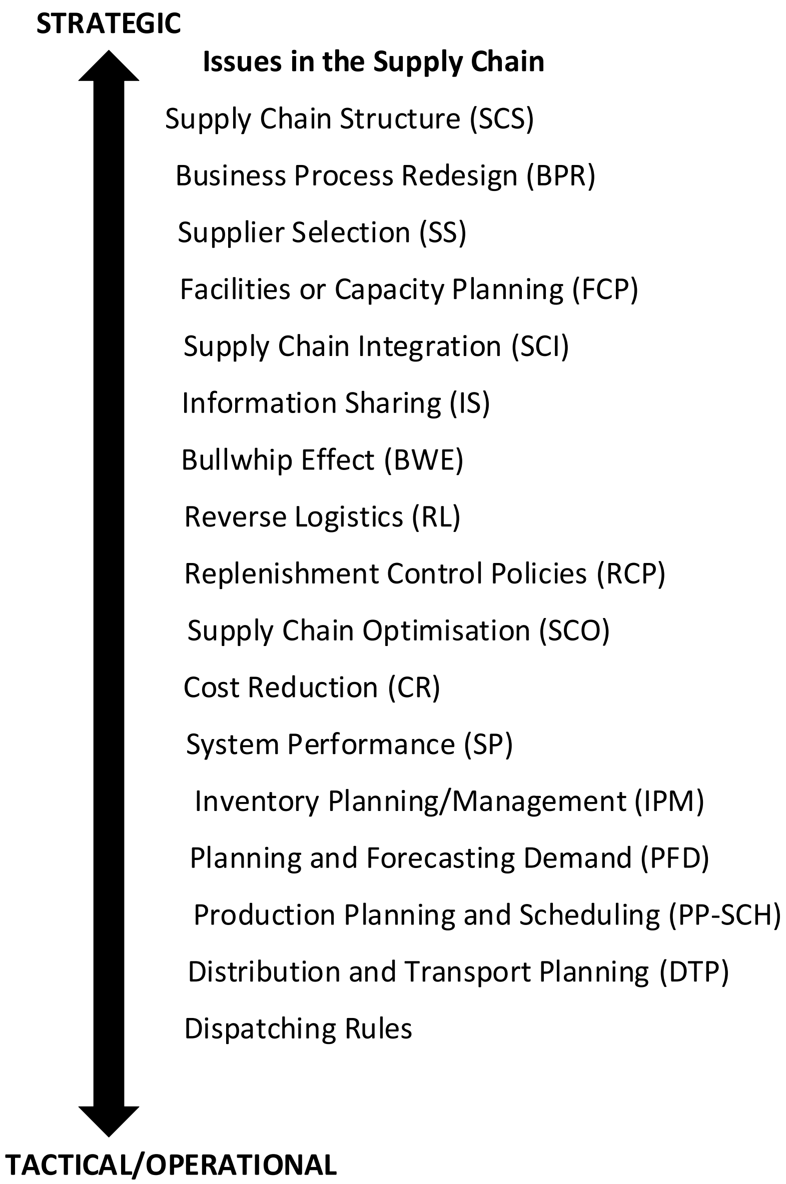


Figure 3.1: Classification of supply chain issues (Tako & Robinson, 2012)

Tako and Robinson (2012) made comparisons between discrete events and systems dynamics simulation. The authors maintain that systems dynamics is more suitable for modelling strategic issues in the supply chain and discrete events simulation for tactical/ operational issues. However, in arguing which method of simulation to choose to model a problem, Behdani (2012) and Savrasov (2008) argued in favour of considering the problem in the microscopic, macroscopic and mesoscopic levels of aggregation.

Table 3.3: The different types of simulation

Authors	Simulation	Advantages	Disadvantages	Uses
(Tarokh & Golkar, 2006)	Spreadsheet	• Simple as they involve the use of a spreadsheet to represent the model, do the sampling and perform computations • File formats are standardized, hence developers can easily pass models from one to the other	• Only simple data structures are available • They are static models, hence they have a weakness in determining time based variances and actions of separate elements. • Complex algorithms are difficult to implement. • They are slower than some alternatives. • Data storage is limited.	• Stochastics models. • Sensitivity analyses
(Borshchev & Filippov, 2004)	Dynamic Systems modelling (MATLAB, SIMULINK)	• Integrated variables have a direct physical meaning. Inherently continuous and are not aggregates of any entities. • Mathematical diversity can be higher than systems dynamics. • Tools used can easily solve systems dynamics problems with much better accuracy.	• They have been designed to be embedded in the engineering design cycle and they do not support the way systems dynamics modellers think.	• Electrical, mechanical and chemical engineering as a standard part of the design process
(Tarokh & Golkar, 2006)	Business games (Beer Distribution Game, Cider game)	• May be used in both education and research • Allow for supply chain awareness i.e. the use of simulation to understand the whole supply chain as opposed to focus on own company only • Allows for development and validating improvements to the current supply chain.	• They are mostly designed for education purposes	

Savrasov(2008) explained these three levels of detail in the context of discrete events simulation, systems dynamics and agent-based simulation. Table 3.4 summarises the classifications by Savrasov (2008).

Table 3.4: Microscopic, macroscopic and mesoscopic level of aggregation in simulation (Savrasov, 2008)

Attribute	Microscopic	Macroscopic	Mesoscopic
Level of detail	Objects and resources are highly detailed in their description	Does not deal with one particular object but with an aggregated set of objects which flow from one stock to the other with strength defined by flow variables.	"Discrete time/continuous quantity"- shows only discrete changes of corresponding continuous flows.
Conduction of experiments	Each experiment needs a number of runs and only after that the data could be aggregated to get the final result.	Useful for experiments of the type 'what-if'	No need for a lot of runs for the experiment.
Example simulation methods	Discrete events simulation and Agent Based Modelling	Systems Dynamics	None so far
Software examples	Arena, AnyLogic, FlexSim, Witness, Netlogo, RePast	VenSim, PowerSim, iThink, AnyLogic	None so far
Disadvantages	• High resource requirements (staff, special software, time) • High level of developers' subjective system presentation. • A set of runs should be performed for each experiment to get results due to the stochastic environment.	• Simulation results are presented as graphs of the process and they are not as representative as simulation on the microscopic level. • There is no flexibility as there is no possibility of changing the algorithm of the system during simulation which may cause problems if the model is not similar to the real world system.	• Theoretical background has not yet been implemented fully. • There is no specialised software.
Advantages	• Graphical representation of model could be developed for model validation and for detecting problems and bottlenecks.	• Very complex systems can be modelled and both qualitative and quantitative factors can be taken into account. • Graphs of processes are useful for whole system understanding.	• Models can be created faster than microscopic level. • No need for a lot of runs for an experiment. • The result is more precise than the macro level as the system algorithm is modelled in high detail. • Models are created faster and are uses for tactical and operational level.

In concluding their paper, Behdani (2012) emphasised that "it might not be necessary to capture all complexity dimensions of a supply chain in every modelling effort; however, when we choose a simulation paradigm or when we make some simple assumptions to reduce the complexity of a system in the model development process, we must be fully aware of complexity dimensions that are influenced by decisions we make". It is obvious that no simulation can capture all aspects of a supply chain because of its global complexity and the fact that a supply chain is not a stand-alone entity as it is also part of other supply chains. What simulation does is to try to imitate the real-world system as much as it can.

After defining the levels of aggregation in simulation modelling, it is necessary to distinguish between the three common methods of simulation. Table 3.5 summarises opinions of various authors regarding discrete events simulation, systems dynamics and agent-based modelling.

Table 3.5: Discrete events, systems dynamics and agent-based modelling

Attribute	Authors	Discrete Events Simulation	Systems Dynamics	Agent Based Modelling
Orientation	(Behdani, 2012)	Process-oriented; focus is on modelling the system in detail	System-oriented; focus is on modelling the system observables	Individual-oriented; focus is on modelling the entities and interactions between them
Entity types	(Behdani, 2012)	Homogeneous	Heterogeneous	Heterogeneous
Level of aggregation	(Savrasov, 2008) (Behdani, 2012)	Microscopic with non-intelligent passive entities moving through the system.	Macroscopic	Microscopic with active entities that can make sense of the environment and interact with others.
Driver for dynamic behaviour	(Behdani, 2012) (Owen, Albores & Greasley, 2010)	Event occurrence	Feedback loops	Agents' decisions and interactions
Mathematical formalisation	(Behdani, 2012)	Event, Activity and Process	Stock and Flow	Agent and Environment
Handling of times	(Behdani, 2012),(Owen et al.,2010),(Savrasov, 2008)	Discrete	Continuous	Discrete
Experimentation	(Behdani, 2012)	By changing the system structure	By changing the process structure	By changing the agent rules and system structure
Flexibility	(Behdani, 2012) (Savrasov, 2008)	System structure is fixed	Process is fixed	The system structure is not fixed
Approach	(Owen, Albores & Greasley, 2010)	Bottom up open loop models suitable for operational and planning areas	Top down approach used for planning problems with a long time frame and strategic or policy level problems	Bottom up models useful for analysing planning and operational problems
Supply Chain themes covered	(Owen *et al.*, 2010)	Modular supply chain planning, logistics, information sharing, supply chain optimisation, modelling control elements	Impact of demand amplification on transport costs, Reverse Supply Chains, Impact of batching on Bullwhip, Quality perception, e-collaboration, performance metrics	Information sharing, supply chain optimisation, modelling control elements, human behaviour and trust, customer collaboration, human behaviour on Bullwhip, market dynamics

3.2 Modelling the bullwhip effect

Just as there are many methods of modelling supply chains, there are also various ways of modelling and quantifying the BWE in a supply chain. Wang and Disney (2016) mentioned three ways of conducting research on the BWE:

- **Empirical studies where** historical data on demand, sales, shipments and production is collected and analysed. It is not only efficient in detecting the BWE but it also allows for pinpointing of underlying causes and for testing of hypotheses.
- **Experimental research** uses laboratory experiments and management games to examine factors that affect the BWE. Mostly focuses on behavioural, psychological and cognitive aspects of decision-makers with regard to their forecasting replenishment or capacity setting behaviour. When properly designed, this method can be used for learning processes as it allows for theories to be tested in isolated and controlled environments.
- **Mathematical modelling** provides the ability to quantify BWE and its causes and to predict the response of the system to various types of disturbances and to offer guidelines for prevention and elimination. Mostly solved analytically. Simulation offers a chance to tackle more realistic bullwhip problems numerically and computationally when model complexity is beyond analytic capability

Whilst all three methods have been applied in literature, various methods have streamed from the mathematical modelling approach to the BWE. Table 3.6 summarises the ways of modelling the BWE mathematically.

Each of the methods stated in Table 3.6 has both advantages and disadvantages depending on the nature of the problem being modelled and considered.

3.3 Why systems dynamics?

For various reasons systems dynamics was selected as the methodology for mathematically modelling the problem in this research:

- Systems dynamics can be applied to processes where only base data is available. System dynamics is being used to mimic the system behaviour and provide quantitative as well as qualitative results in a 'what-if' analysis situation.
- Systems dynamics not only accounts for delays, but unlike discrete event simulation and agent-based modelling it also provides feedback on relationships.
- It develops causal relationships with feedback that allows the generation of data to get parameter values.
- This research focused on measuring supply chain performance by analysing the flow of products between echelons. It was not interested in single product characteristics or queues, hence it was necessary to model the system at the macroscopic level. Systems dynamics is usually the most preferable type of simulation for modelling problems at the macroscopic level.
- The complexity of the closed-loop supply chain required a more aggregated approach to system analysis hence the selection of systems dynamics as a method for modelling the problem at hand.
- Between Discrete Events, Agent-based Based Modelling and Systems Dynamics, Systems Dynamics, is the only type of simulation that has been recorded in literature for being able to "demonstrate the BWE" (Tarokh & Golkar, 2006).
- It can model both supply chains and the bullwhip effect.

Table 3.6: Ways of mathematically modelling the BWE

Author	Method	Description
(Geary, Disney & Towill, 2006) (Riddalls, Bennett & Tipi, 2000) (Disney & Lambrecht, 2008)	'What-if' simulation	• Systems dynamics modelling where causal loop diagrams are transformed into simulation models and transformed via test demands. Dynamic response is explicit. • Explicitly possible to model such things as capacity constraints non-negative inventory and WIP. • Strengths are in qualitative investigation of what if scenarios
(Geary *et al.*, 2006)	Operations Research Theory	• The problem is expressed as a difference math equation with some parameters variable and a solution is sought to minimise a cost function for an assumed set of operating conditions. • Dynamic performance is implied by a mathematical solution to the problem.
(Geary *et al.*, 2006) (Disney & Lambrecht, 2008)	Filter theory	• The problem is expressed in the frequency domain and value judgements are made on spectrum widths of the "message" and the "noise" or "disturbances". A control law is assumed and solution is assumed by shaping the system frequency to the needs of the user. • For H-infinity control, an attempt is made to make sure that the system responds to all frequencies with an amplitude ratio of less than infinity. Such systems are highly damped and the Ideal filter approach compensates for this.
(Geary *et al.*, 2006) (Disney & Lambrecht, 2008)	Control theory	• The problem is expressed in transfer function form and concentrates on system structure to guarantee stability and to generate the desired shape. • It is represented by the Laplace transform in the continuous time and the Z transform in the discrete time. • They work well if the system is linear, time invariant, the system has no initial conditions and single input single output scenarios.
(Disney & Lambrecht, 2008)	Differential Delay Equations	• Used in systems that contain pure time delay in them for example in supply chain settings where there is a transportation delay.
(Disney & Lambrecht, 2008)	Fourier Transform	• Frequency response method where a time series is broken into a series of harmonics. Harmonics are sine waves of different amplitudes and phase lags. • Understanding how replenishment rules respond to the spectrum of harmonics allows to understand how they react to the demand signal.

3.4 Data collection and analysis method selection

Meredith (1998) distinguished between rationalist research and case research in terms of operations management research. The author states that in rationalist research, "relationships and observations are considered to be independent of the theories used to explain them and hence can be studied, manipulated at will and controlled as needed by the researcher". Common methods in rationalist research were also mentioned and these include equations, laboratory experiments and statistical survey analysis. In a similar way, Meredith (1998) mentioned that , "a case study typically uses multiple methods and tools for data collection from a number of entities by a direct observer(s) in a single natural setting that considers temporal and contextual aspects of the contemporary phenomenon under study, but without experimental controls or manipulations". Bonoma (1985) emphasises that the goal of case study research "is to understand as fully as possible the phenomenon being studied through perceptual triangulation". Advantages and disadvantages of the rationalist and case research were also identified by Meredith (1998) and they are summarised in Table 3.7.

Whilst the use of simulation is beneficial for the 'what-if' scenarios of this research, it is also beneficial to combine the artificial method with empirical knowledge i.e. knowledge based on real-world observations or experiments. This means that although this research can be classified as rationalist, it adopted some aspects of case research. Flynn et al. (1990) listed the main benefits of empirical research in production and operations management:

- Can be used for documenting the state of the art in operations management.
- Provide a baseline for longitudinal studies.
- Can be invaluable in the development of parameters and distributions for mathematical simulation studies.
- Theory building and verification.

Table 3.7: The rationalist and case research (Meredith, 1998)

Rationalist Research	Case Research
Advantages	
• Precision that it can achieve in its variables, and thus offers testability and reliability. • Knowledge and wide acceptance of its standard research procedures (model formulation, variance reduction techniques, and sample size) particularly in operations management.	• Phenomenon can be studied in a natural setting and meaningful relevant theory generated from the understanding gained through observing actual practice. • The case study allows the why question to be answered with a relatively full understanding of the nature and complexity of the complete phenomenon. • It lends itself to early exploratory investigations where the variables are still unknown and the phenomenon not at all understood.
Disadvantages	
• Most trivial data • Sampling difficulties, the great majority of quantitative studies based on sampling use samples of convenience or opportunity. • Research cannot produce information that goes beyond the model such as anomalies. • The distribution restrictions of statistics such as normality. • Abstract and remote character of key variables meaning the lack of comparability across studies. • Failure to achieve much predictive validity.	• Requirements of direct observation in actual contemporary situation (cost, time and access hurdles). • The need for multiple methods, tools and entities for triangulation. • Complications of context and temporal dynamics. • Lack of familiarity of its procedures and rigour.

All the benefits listed by Flynn et al. (1990) are applicable to this research. This research seeks to develop mathematical distributions and parameters for the systems dynamics modelling from real companies. It also hopes to develop some theories on capacity limitations as well as test some hypotheses by previous authors on the BWE in closed-loop supply chains. As a result of these needs it was necessary to find a research design that could be used to obtain data for empirical research.

Flynn et al. (1990), Meredith (1989) and Ellram (1996) explained the various methods for empirical research. Ellram (1996) focused on how the research questions affect the methodology used for empirical data as stated by Yin (1994). The various methodologies, the questions they answer and their use in operations management are summarised in Table 3.8.

Table 3.8: Empirical research methods (Flynn et al.(1990), Meredith et al. (1989) and Ellram (1996))

Method	Description	Objective	Questions answered	Uses in operations
Single case study	• Documents in detail the operations of a single plant. • Neither independent nor intervening variables are controlled but various outcomes are measured extensively and systematically.	Qualitative Explanation Description exploration	Who, what, where, how, why	• Preliminary or pilot in multiple case studies • When case is extreme, unique or has something special to reveal
Multiple case study	• Detailed information is gathered at multiple sites • In analysing data, similarities and differences between the sites are noted and documented to the extent possible.	Qualitative Explanation Description exploration	Who, what, where, how, why	• Theory building and theory verification • Useful for descriptive research where the focus is on a specific phenomenon. • Research questions about process
Field experiment	• Researcher manipulates the independent variable of the natural setting and systematically observes the resulting changes	Qualitative Explanation Description exploration	Who, what, where, how, why	• Theory building and theory verification
Panel study	• Obtains the consensus of experts	Quantitative Prediction	Who, what, where, how many, how much	• Useful in defining terms and making predictions.
Focus group	• Similar to panel group but the group is physically assembled and each response is given to the group orally, rather than in written form.	Quantitative Prediction	Who, what, where, how many, how much	• Useful in defining terms and making predictions
Surveys	• Relies on self-reports of factual data. • Allows for statistical analysis	Quantitative Prediction Description Exploration	How, often, how much, how many, who, what, where	• Comparing innovations • Study of process and method implementation
Action research	• Requires the researcher to be involved in the phenomenon under study. • Differs from field experiment in that complete factorial design is not attempted or desired.	Qualitative Explanation Description Exploration Prediction	How, why, who, what, where	• Method and time studies
Structured interview	• Observation is limited to interview process and transcripts • Main reason is to control the situation and responses, thereby ensuring uniformity in analysis	Quantitative Prediction Description Exploration	How, often, how much, how many, who, what, where	• Issues in manufacturing strategy • Competition in high velocity environments.
Historical/ archival analysis	• Examines historical documents or less formally recorded data. • No manipulation of variables is possible, the only control the researcher has is that of selecting and calling for particular evidence.	Quantitative Prediction Description Exploration	How, often, how much, how many, who, what, where	• Analysis of written communications in a firm • Analysis of utilisation, cost or productivity data. • Evaluation of factors, comparisons and make inferences

3.5 Empirical research method selection

In this research, a multiple case study combined with the laboratory experiment approach will be adopted in the design. A multiple case study is necessary because;

- The research will make comparisons of independent closed-loop supply chains with different products and different remanufacturing capacities and return patterns.
- From the research questions in Chapter 1, the research aimed to answer 'How' and 'Why' questions and according to Yin (1994), case studies are most appropriate for answering such questions.
- Some hypotheses are being tested and some theories developed in this research hence the necessity for case studies.

In a similar manner, the use of laboratory experimentation was added because a case study research rarely controls observations. This research was not just centred on observing the state of the art of a system. This research measured the BWE in the closed-loop supply chain under its current situation and tried to predict outcomes of changing some parameters on the system, which required the use of controlled experiments. A 'what-if' analysis is the strength of system dynamics and it could not be carried out without controlling some aspects of the investigation. Some parameters were varied in the sensitivity and 'what-if' analyses.

3.6 Conclusion

The chapter justified the methodology selection of the research. Systems Dynamics, Multiple case study and experiments are necessary for the problem at hand. Chapter 4 explains the selected methodologies in detail, listing the stages to be followed in applying these methods to the research.

CHAPTER 4
STAGES IN SELECTED RESEARCH METHODOLOGIES

After selecting the appropriate method for modelling the research problem depending on the conditions and assumptions, there is a need to explain the stages in the development of a system dynamics model as well as case study design. This is done to give an understanding of the processes before applying the same process to the problem at hand. This chapter serves to explain the stages in the research methodologies selected before they are applied to the problem. The two methodologies of systems dynamics modelling and case study research design are carefully explained in sections within this chapter.

4.1 Stages in system dynamics modelling

Oral and Kettani (1993) emphasised the main stages used in the system dynamics modelling process and equate them to the generic operations research modelling, although different terminology may be used. Systems dynamics model development follows four main stages;

- Model conceptualisation
- Model formulation
- Model testing and implementation
- Policy recommendations

In addition to the stages listed by Oral and Kettani (1993), Sterman (2000) summarises the stages in systems dynamics modelling. The processes summarised by Sterman (2000) are shown in Figure 4.1. He emphasises that “modelling is embedded in the dynamics of the system. Effective modelling involves constant iteration between experiments and learning in the virtual world and experiments and learning in the real world”.

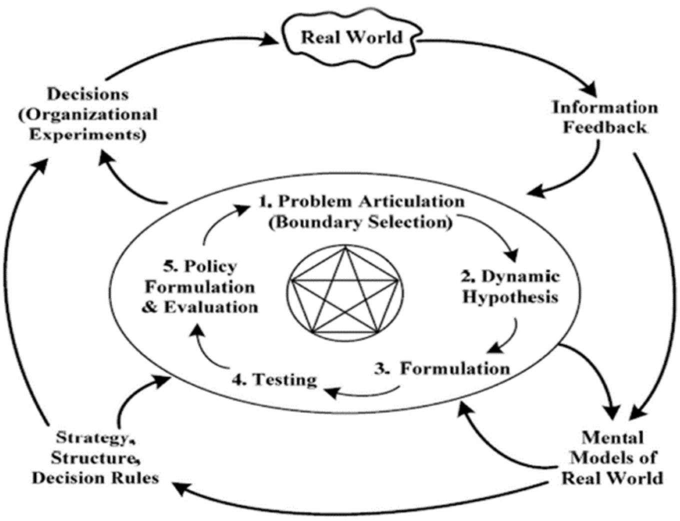


Figure 4.1: The modelling process (Sterman, 2000)

To summarise the definitions of Oral and Kettani (1993) and Sterman (2000), a list of stages in the simulation modelling process is represented in Figure 4.2. Model conceptualisation and formulation will be explained in Chapter 5 as well as the model testing. Implementation of the model is described in detail in Chapter 6 after defining the case studies.

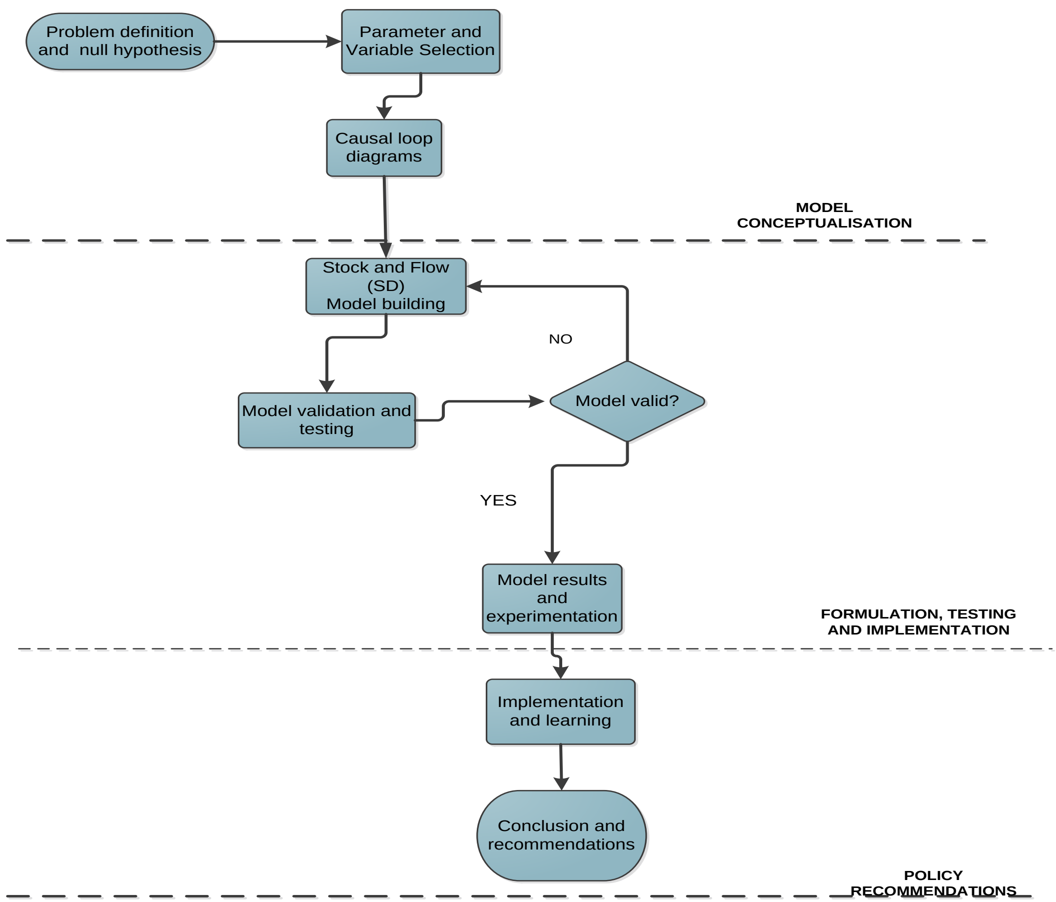


Figure 4.2: Stages in systems dynamics modelling

The null hypothesis and the definition of the problem was stated in Chapter 1 when the problem was first introduced.

4.1.1 Parameter and variable selection

This is the process of defining the initial condition of the system i.e. the base data of the case under study. The process also includes defining the scope of the system as well as the dependent and independent variables. Model assumptions and their implications on the design of the model are also listed. This stage involves the development of the model boundary chart. "A model boundary chart summarizes the scope of the model by listing which key variables are included endogenously, which are exogenous and which are excluded from the model" "(Sterman, 2000). The same author further explains three types of variables:

1. **Exogenous variables** arise from 'without'. These are controlling variables and they cause a change in the behaviour of a system by affecting other variables within the system. They are also called independent variables. Examples include the inventory cover times and adjustment times. These two variables affect the inventory adjustment and the bullwhip effect but the bullwhip effect can never affect these two variables.
2. **Endogenous variables** arise from 'within'. Endogenous variables are the ones that change the state and they are important in the analysis of system behaviour as they are affected by other variables within and outside the system. An example of such a variable is the inventory discrepancy which is affected by the inventory level and the desired

inventory level and it affects the number of orders placed by each echelon which in turn will affect the bullwhip effect.

3. **Auxiliary variables** aid in the clarity and communication of the system. They consist of constants and functions of stocks. Examples of such a variable include the shipment time.

A subsystem diagram as described by Sterman (2000) is also developed in this stage. Subsystem diagrams model the overall architecture of a model and they convey information about the boundary and level of aggregation in the model. They also communicate some information about the endogenous and exogenous variables.

4.1.2 Causal loop diagrams

Sterman (2000) explained that causal loop diagrams show how the variables are related with arrows pointing from a cause to an effect. Variables are related by causal links. Each link is assigned a polarity, either positive or negative that shows how the dependent variable changes when the independent variable changes. Causal loop diagrams represent the feedback structure of the system. Figure 4.3 gives an example of a causal loop diagram. Causal loop diagrams will be used to represent relationships between variables and parameters in the research, which will be used in establishing mathematical relationships for the model. For example in Figure 4.3, the distributor's orders backlog decreases with an increase in the orders placed by the distributor.

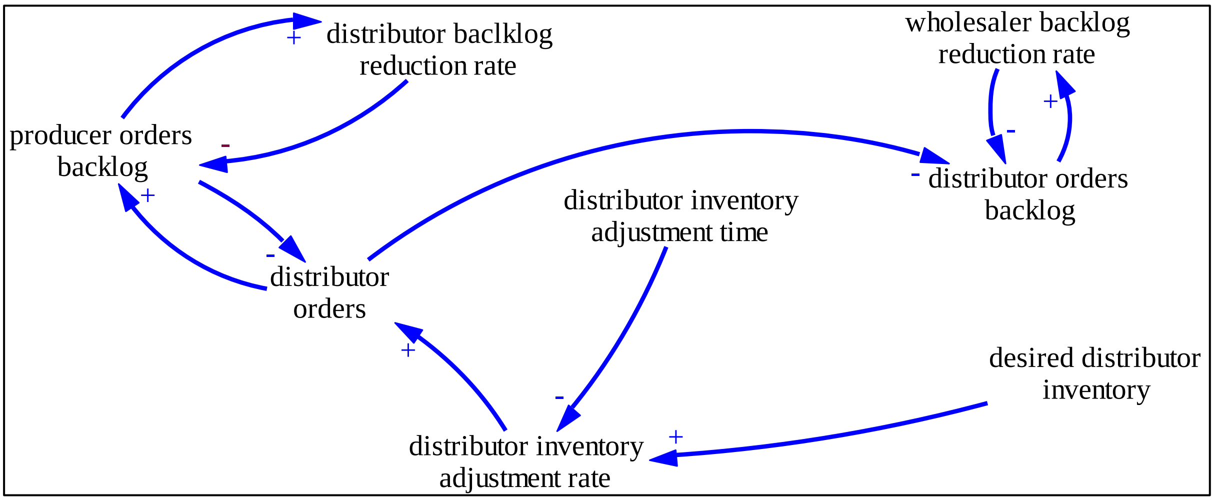


Figure 4.3: Causal loop diagram example

4.1.3 Stock and flow diagrams

While causal loop diagrams emphasise the feedback structure of a system, stock and flow diagrams emphasise their underlying physical structures. In the model building stage, stock and flow diagrams are developed. An example of a stock and flow diagram is represented in Figure 4.4. According to Sterman (2000) stock and flows track accumulations of material and information as they move through the system. Stocks include inventories of products while flows are the rates of increase or decrease in stocks.

From the realm of diagrams, in the model building stage, a formal model is developed with complete equations, parameters and initial conditions. Equation 4.1 is an example of an equation in the formalisation stage of a systems dynamics model.

$$raw\ mat\ inventory\ (t) = raw\ mat\ inventory(t - dt) + (-comp\ prod\ rate) * dt \qquad (4.1)$$

From equation 4.1, *raw mat inventory* represents the raw material inventory, *t* is the present time under investigation, *dt* is the unit change in time and *comp prod rate* means the component production rate.

Formalisation helps in identifying some overlooked concepts within the model.

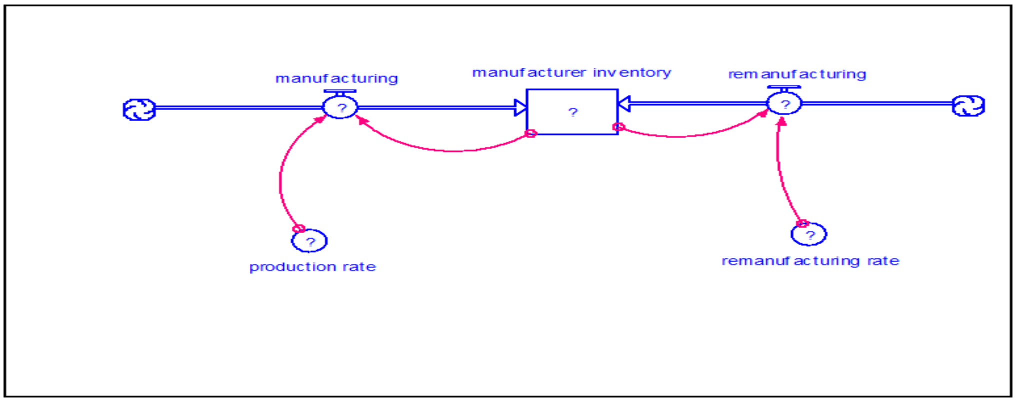


Figure 4.4: Stock and flow diagram example

4.1.4 Model validating (testing)

Testing is when the simulated behaviour of the model is compared to the actual system, when the dimensional consistency of equations is checked and the sensitivity of the model behaviour under different conditions is analysed. Sterman (2000) emphasises that models must be tested under extreme conditions that may never have been observed in the real world to help in discovering flaws in the model and set the stage for improvement and understanding. In this method a white-box approach to model validation will be used. White-box validation tests internal structures or workings of a program, as opposed to the functionality exposed to the end user. In white-box testing an internal perspective of the system, as well as programming skills, are used to design test cases. The tester chooses inputs to exercise paths through the code and determine the appropriate outputs.

4.1.5 Model results and experimentation

After developing confidence in the model, the model was used to design and evaluate scenarios for improvement through what is known as a 'what-if' analysis. Experimentation should not be only about changing values for parameters but creating entirely new structures and decision rules as well.

4.1.6 Implementation and learning

This stage is almost similar to the experimentation and it emphasises the iterative nature of models. The more experiments that one carries under different scenarios, the more knowledge one gains. This stage also analyses the results from the experiments.

4.2 Stages in case study and experimental research design

As stated in Chapter 3, this research combines the case study method with the experimental method as it aims to answer 'how' and 'why' questions whilst at the same time trying to control some of the variables for use in the systems dynamics simulation. Kirk (2013) mentioned the main goal of an experimental design as establishing connections between dependent and independent variables and to get as much information using the least amount of resources. Case studies have a 'no control' aspect, hence they were combined with experimental design for 'what-if' if and sensitivity analyses. Figure 4.5 shows the stages in the combined case study and experimental design. The stages were adopted from original stages by Rose, Spinks and Canhoto (2015) and Kirk (2013). The stages in Figure 4.5 are explained in the following sections.

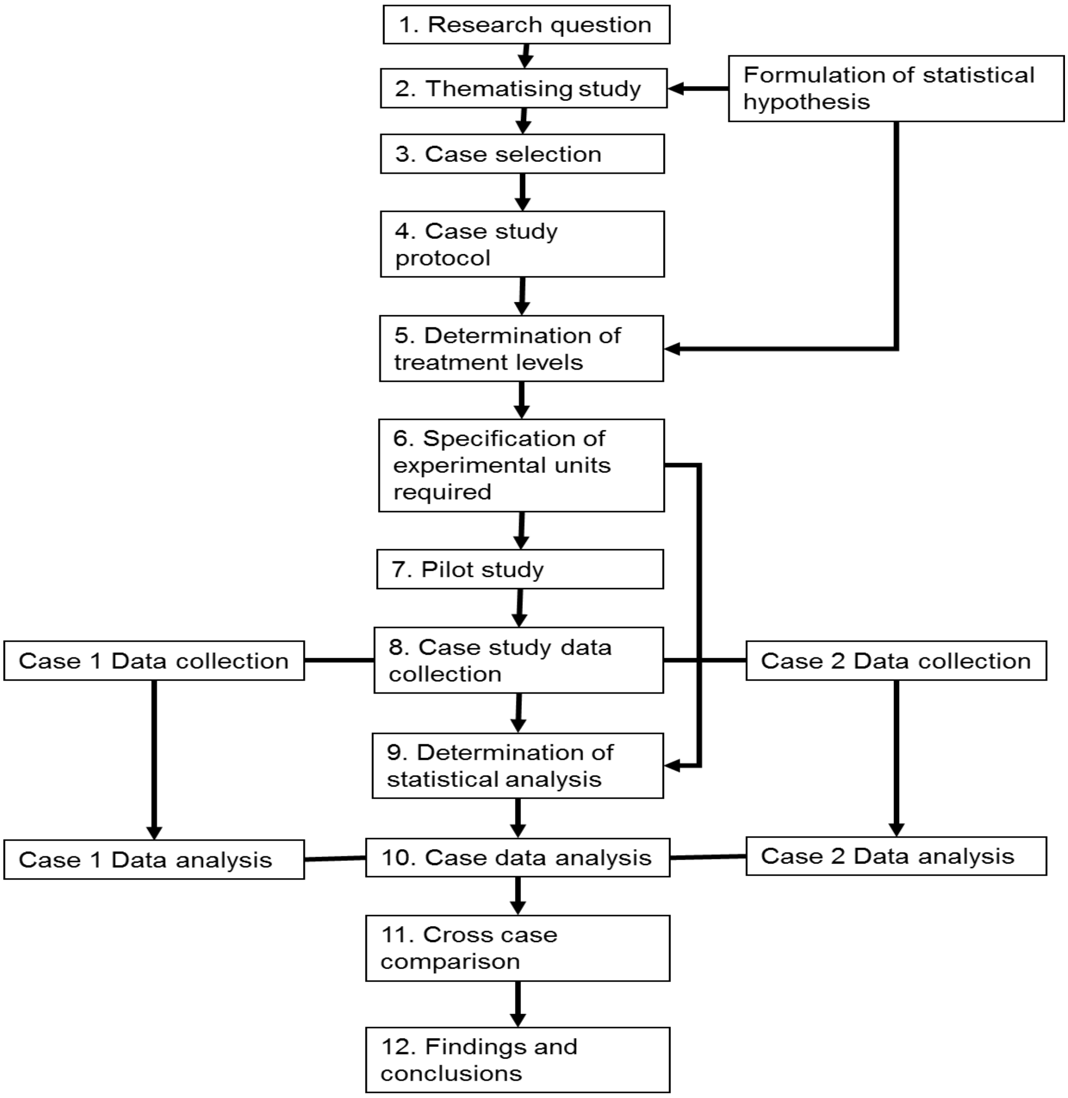


Figure 4.5: Stages in combined case study and experimental design (Rose, Spinks & Canhoto, 2015) **and (Kirk, 2013)**

4.2.1 Formulating the research question

The research question shapes the structure of the studies. This helps to clearly define what the cases in the case study research will be i.e. whether they are individuals, organisations, events and so on. The research question also makes it clear what aspects of the cases the research is interested in. Based on the research questions asked in Chapter 1, for example, the unit of analysis in this research is an entire supply chain network that has a reverse logistics operation and the unit of analysis is a BWE measurement.

4.2.2 Thematising the study

This was done in Chapter 2 of the literature review. Literature was used to identify research gaps and to develop theoretical propositions and hypotheses to be tested in the research. In this case, theory was used as an initial guide to design and data collection. This helped in creating a research direction that takes into account existing knowledge in the area.

4.2.3 Selecting cases

This involved determining what cases and how many case studies were to be used for the research. This research used multiple case studies for comparative purposes.

4.2.4 Developing the case study protocol

"A case study protocol is a written statement of what you are trying to achieve and how you are planning to achieve it, it serves as a project plan for your case study field work" Rose et al. (2015). According to the same author, preparing a case study protocol should:

- Allow one to anticipate potential problems in the proposed research so that one can devise strategies in advance for dealing with them.
- Should provide a link between the research questions, the data needed to answer these questions and analysing data.

Table 4.1 shows a sample case study protocol as described by Rose et al. (2015).

Table 4.1: A sample case study protocol Rose et al. (2015)

Topic	Contents
Overview	A statement of the overall aims of the research.
Field procedures	The procedures to be adopted during the field research. These include how to gain access, how to capture data, time plan for data collection, etc. for each case.
Research questions	The specific research questions should be stated, including clear links to the theory/literature where appropriate.
Data collection matrix	A matrix (table) can be used to show the types of evidence to be collected, along with their relationships to each other and to the research questions identified above.
Data analysis and case study reports	How you will analyse individual cases, conduct cross-case analysis and create the case study reports.

4.2.5 Determination of treatment levels

This is a stage where the researcher determines the independent variables to be manipulated, measurements to be recorded, the dependent variables and nuisance variables to be controlled.

4.2.6 Specification of the number of experimental units required

The researcher has to determine the total number of runs required for each sample data or whether a full factorial experiment is necessary or not depending on the cost and necessity of a full factorial experiment.

4.2.7 Pilot study

"The purpose of a pilot study is to explore both substantive topic and method issues. It can help to sharpen the focus of the research as well as ensure that the intended field procedures are effective" (Rose *et al.*, 2015).

4.2.8 Case data collection

When using multiple case studies, a uniform way of recording data should be used as this will help with both analysis and reliability. A case study database is also set up to manage the evidence that is collected, whether this evidence is in electronic or paper format. The database can also act as a repository for emerging ideas, for example initial thoughts on possible answers to the research question.

4.2.9 Determination of statistical analysis to be used

This includes the decision on the use of statistical software for data analysis and whether or not to use descriptive statistics. Depending on the number of variables, the researcher will decide on the use of data analysis using tools like regression analysis, MANOVA and ANOVA. Statistical analysis will determine the significance of factors as well as interactive effects of factors under consideration.

4.2.10 Case data analysis

"Analysis can proceed iteratively with data collection, although one should be careful to avoid 'premature closure' by reaching conclusions too early without thorough evaluation of all of the data" (Rose, Spinks & Canhoto, 2015).

4.2.11 Cross-case comparison

If the study involves multiple cases, cross-case analysis can be carried out once the analysis of individual cases is completed.

4.3 Conclusion

The main purpose of this chapter was to explain in detail the main stages followed in applying selected methodologies for this research. The selected methodologies are case study, systems dynamics and the experimental method. The next chapters show these main stages in play during the course of this research. Chapter 5 begins by explaining the simulation design stage of the research.

CHAPTER 5
SIMULATION MODELLING AND MODEL TESTING

This chapter explains the systems dynamics model development used in the research. The model focuses on closed-loop supply chains that have collection and remanufacturing capacity constraints. Under the process of model formalisation, a model should also be verified and validated to see if it mimics or behaves like the real-world system before any experiments can be carried out using the model. Before describing the case studies and designing the experiments, this chapter explains the simulation models as well as the various tests carried out in verifying and validating the models.

5.1 Model conceptualisation

The conceptualisation stage involved identifying the problem and stating the null hypothesis, variable and parameter selection and making causal loop diagrams to identify variables and parameters that have a notable impact on each other. These three main components of the conceptualisation stage are explained in the next sections.

5.1.1 Identifying the problem

The research aims to model a closed-loop system that is made up of components inventory, serviceable inventory, distributor's inventory, wholesaler's inventory, retailer's inventory and the demand. These inventories were affected by the process of reverse logistics in different ways and this affected the bullwhip effect. The inventory management techniques and production capacities are based on data from case studies that are explained in Chapter 6. There were three propositions and four hypotheses for this research. These hypotheses and propositions were introduced in Chapter 1 and they are summarised in Table 5.1.

Table 5.1: Theoretical propositions and research hypotheses

Theoretical Proposition	Research Hypotheses
Theoretical Proposition 1 Increasing the remanufacturing lead time (the time from which the product is collected until it can be sold again as serviceable inventory) and residence time (the time that the customer keeps the product before returning it for remanufacturing) increases the BWE.	**Hypotheses** • Increasing the time that the product stays with the customer before being returned introduces material delays which will impact the BWE in the forward chain. • The more time it takes to carry out reverse logistics activities such as remanufacturing, collection and inspection, increases material delays which may increase the BWE in the forward chain.
Theoretical proposition 2 Increasing the remanufacturing percentage decreases the BWE.	**Hypotheses** An increase in the amount of products accepted for remanufacturing can reduce variabilities in the component, raw material and retailer stock which may reduce the BWE in the forward chain.
Theoretical Proposition 3 Capacity limits in terms of collection and disposition may lead to delays which can increase remanufacturing lead time and lead to an increase in the Bullwhip effect.	**Hypotheses** Collection and remanufacturing capacities may not be equal and these differences may result in delays which will increase the lead time and lead to an increase in the BWE in the forward chain.

5.1.2 Model assumptions and boundaries

A model boundary chart in Table 5.2 shows the exogenous and endogenous variables of the models as well as the excluded variables. The assumptions used in building the models are listed below:

- The models assumed a serial forward and reverse network as opposed to the divergent and convergent models listed by Beamon and Chen (2001). This was because supply chain structure in terms of echelons, although listed as one of the causes of the BWE was not included in the boundary of the model. (See Table 5.2).
- The models did not measure any soft variables. Coyle (2000) defined a soft variable as "a variable that is hard to measure as precise numerical data, for example mental data, human judgement, expectations and confidence levels". The models did not measure behavioural causes of the BWE.
- Each supply chain model was composed of one product although products may differ between case studies. Products were permitted to differ between case studies because of the difficulty to find organisations with closed-loop supply chains.
- The research only measured supply chain performance from the operations perspective and not from the financial perspective. This meant that it did not look at supply chain costs, contracts and profits.
- The models did not consider products returns inside echelons or between echelons of the forward chain. This meant that it did not consider production returns, returns by retailers and distributors to suppliers and product recalls by the manufacturer.

- All products, new and reprocessed were sold in the same market.
- Recycling was only considered if the material recovered is used to make the original product from which the used material was recovered as opposed to when the recovered material was used to make an entirely different product.
- The supply chain player responsible for the collection of used products was also responsible for their transportation.
- The supply chain players responsible for the reprocessing of products were also responsible for their inspection.

Table 5.2: Model boundary diagram

Endogenous Variables	Exogenous Variables	Excluded variables
• Inventory discrepancy • Remanufacturing lead time • Used products	• Inventory adjustment time • Inventory cover time • Residence time • Collection percentage • Remanufacturing percentage • Collection capacity • Remanufacturing capacity	• Supply Chain profits • Supply Chain costs • Supply Chain structure • Soft variables • Behavioural causes of BWE • The supplier and the supplier's suppliers.

5.1.3 System description

The closed-loop system under study assumed that manufacturing and remanufacturing did not share the same plant. This meant that the remanufacturing capacity did not change the production capacity which was kept constant in this system. Inventory management in the forward chain was impacted by the presence of returns as they affected the level of the serviceable inventory. The return of products to the serviceable inventory is what linked the forward and the reverse chain as inventories had to be adjusted to accommodate changes in the serviceable inventory due to the introduction of product returns. The remanufacturing had no impact at all on the fixed production capacity of the forward chain.

It should be noted that the demand was fluctuating and not constant in all periods. This meant that the demand had an impact on the amount of products that were returned in each period. For example, the kitchen appliances described under the case studies in Chapter 6 followed a lognormal demand distribution with a mean of 4 000 products per week and variance 2 000 products per week. This meant that the demand oscillated between 2 000 products per week and 6 000 products per week. Since the retailer only sold what the customer required, then it meant that the amount of product returns also oscillated between 2 000 products per week and 6 000 products per week. Because of this oscillation of demand, it should be noted that with the introduction of remanufacturing and collection capacity limits, there were always periods of remanufacturing downtime even if these two limits were equal because the products returned fluctuated sometimes to less than the available capacities.

Periods of remanufacturing downtime also resulted from the residence time. Since the simulations began with zero inventories (except for raw materials), it meant that the manufacturer started off selling only new products. The presence of returns began after the customer used the product and decided to return the product. Residence time was a factor under investigation. For greater residence times, it meant that it took some time before returns were actually present in the reverse chain and this increased periods of remanufacturing downtime.

5.1.4 Subsystem diagram

A subsystem diagram gives a schematic representation of the supply chain to be modelled. The subsystem diagram for the supply chain under study is shown in Figure 5.1. For the supply chain in Figure 5.1, the manufacturer manufactured products and sent them to the distributor, who then sent these products to a wholesaler. Products from the wholesaler were passed on to the retailer and finally to the end customers. After a product was used, it was either collected by players in the forward chain or by a third party and inspected to determine the disposition strategy. A product could still be good enough to be reused: if it could not be reused, some components could be replaced in the process of remanufacturing. If a product could not be remanufactured, it was torn down to pieces and those parts that could be reused were chosen. Parts that could not be reused could either be remanufactured or recycled. If parts did not suit these purposes then they were incinerated/disposed of.

Five different scenarios were defined:

1. The BWE in an ordinary supply chain with no product returns.
2. The BWE in a supply chain with returns from the customer for either reuse, recycling, refurbishing, cannibalisation or remanufacturing without any capacity constraints for both collection and remanufacturing.
3. The BWE in a closed-loop system with returns from the customer and collection capacity constraints but unlimited remanufacturing capacity. In this scenario products were remanufactured as they were collected, according to the PUSH policy described by Van der Laan et al. (1999).
4. Same as scenario 3 but there was no limit to the collection capacity (all products were collected) but the remanufacturing capacity had a limit. In the case where the collected products were more than the remanufacturing capacity, they were carried forward to the next period. Similarly, when the collected products were less than the remanufacturing capacity, no remanufacturing took place in that period until enough products had been collected for remanufacturing.
5. Same as scenario 3 but both the collection and the remanufacturing capacities were limited.

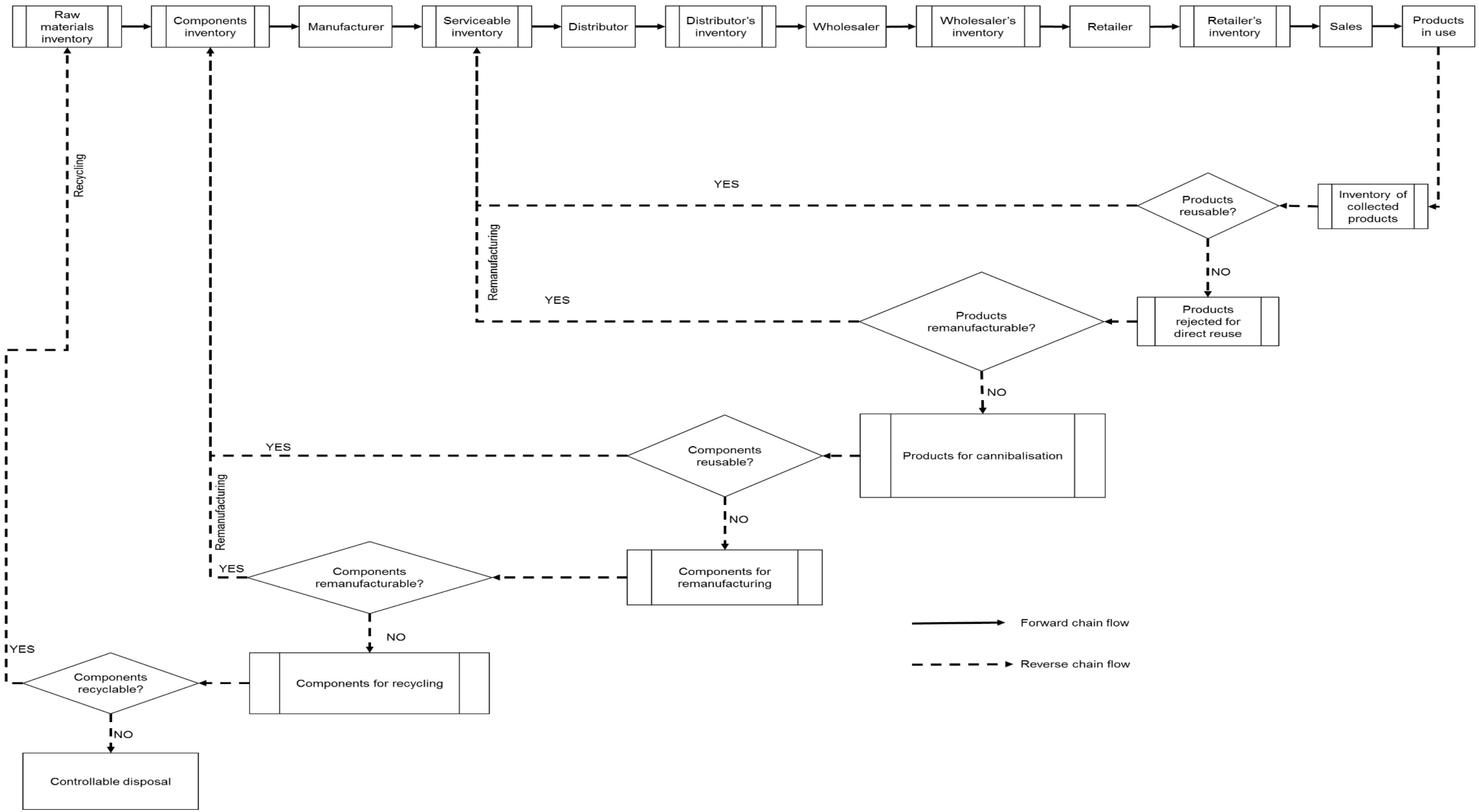


Figure 5.1: Subsystem diagram of supply chain under study

5.1.5 Causal loop diagram

The forward chain begins with the manufacturer who has already procured raw materials from suppliers. The serviceable inventory consists of new products through production. Production introduces new products according to their production time, reused products collected from end customers and remanufactured products through collection and remanufacturing. The intention of the serviceable inventory is to cover as many orders as possible from the distributor through deliveries to the distributor, which needed some delivery time to reach the distributors. Increasing the shipments to the distributor increases the distributor's inventory.

The same process was repeated in the links of the wholesaler and retailer. In these cases however, rather than linking the serviceable inventory with the distributor's inventory, the distributor's inventory was linked with that of the wholesaler and the wholesaler's inventory was connected to the retailer's inventory. All unmet orders were backlogged and were satisfied after a period of time. The retail inventory was intended to meet demand through sales. The sales turned to used products after their product life cycle time (time which the product is designed to be useful) and the residence time (time which the consumer decides to keep the product) that could be collected for reuse, remanufacturing or recycling.

The reverse chain begins when products are collected. The collection of products was limited by the collection capacity of the party responsible for the process. All collected products were sent to the collected products inventory which decreased as products were deemed suitable for reuse. Rejected products for reuse were inspected to see if some components could be replaced and whether they could be reused again. If a component could be replaced then the products increased the products accepted for remanufacturing inventory and decreased the collected products inventory.

The products accepted for remanufacturing inventory was decreased by the remanufacturing rate which was controlled by the remanufacturing capacity, the remanufacturing time and the remanufacturing percentage. An increase in the remanufacturing time decreased the remanufacturing rate, while an increase in the remanufacturing percentage increased the remanufacturing rate. A smaller remanufacturing capacity also decreased the remanufacturing rate. Products that were not accepted for remanufacturing increased the inventory of products rejected for remanufacturing. This inventory was decreased when these products were further torn down to find out if they may have components that could be reused.

An increase in reusable components increased the components inventory while decreasing the inventory of products that could not be remanufactured. If components cannot be reused they are inspected to see if they can be remanufactured. Those components that could not be remanufactured could be recycled for material recovery.

A causal loop diagram was useful for establishing relationships between variables. Figure 5.2 shows the causal diagram used in the conceptual part of the model. The diagram indicated the nature of the links as well, with the positive sign indicating direct proportionality i.e. when one of the variables increased, the one linked to it also increased and vice versa. Similarly for the negative sign, if the value of the variable decreased the one directly linked to it also decreased.

The causal loop diagram was generated in the design stage of the model and it did not include some of the parameters that were required later in the modelling phase, nor did it indicate the nature of the flow or the level of each variable. All of the other information is included in the stock and flow diagram which is found in the model formalisation stage.

5.2 Model formalisation

In the model conceptualisation stage, the model boundaries, assumptions and relationships between some variables are explained. The conceptualisation stage is usually carried out in the design stage of the model. The model formalisation stage however, is the real designing of the model. Activities involved in the formalisation of the model include the construction of stock and flow diagrams, model verification and validation. The model verification and validation processes are explained in Chapter 6.

Based on the causal loop, subsystem and boundary diagrams explained in the preceding sections, stock and flow diagrams for the models are made in addition to the equations forming the model. For the formalisation stage of the model, ITHINK STELLA was used. VENSIM software was used to construct the causal loop diagram because STELLA did not permit the construction of closed loops in terms of polarity of arrows, a trait which could be overcome by VENSIM. In the formalisation stage, the researcher chose STELLA because considering the BWE ratios that were being measured in this research, there was a need to transfer the data to an EXCEL file in order to carry out these calculations and STELLA is more user-friendly in terms of such additional requirements compared with VENSIM.

5.2.1 The forward chain

The forward chain was constructed based on the model explained by Sterman (2000). There is a difference in assumptions made in the models. Some of the differences in assumptions are explained in the following paragraphs.

A company maintained a stock of orders to meet customer demand. Orders that were not met within a certain period are carried over to the next period (backlogged orders). The model began with production of components making up a product. The components were made using inventory of raw materials. The raw material inventory was assumed to be so large that it could not be depleted. The rate at which components were used for product production was an outflow from the raw material inventory and it was determined by the number of components per product, the raw material inventory, the component inventory discrepancy, the components inventory adjustment time, the component production capacity of the company, and the expected distributor's orders. This relationship was represented in equation 5.1.

$$comp\ prod\ rate = max\left(min\left(min\left(\frac{RI}{ct},\left(EDO \times \frac{c}{p} + \frac{CID}{CIat}\right)\right), cc\right), 0\right) \tag{5.1}$$

Where RI is the raw material inventory, ct is the component production time, and EDO is the expected distributor's orders, c/p is the components per product, CID is the component inventory discrepancy, $CIat$ is the component inventory adjustment time and cc is the component production capacity.

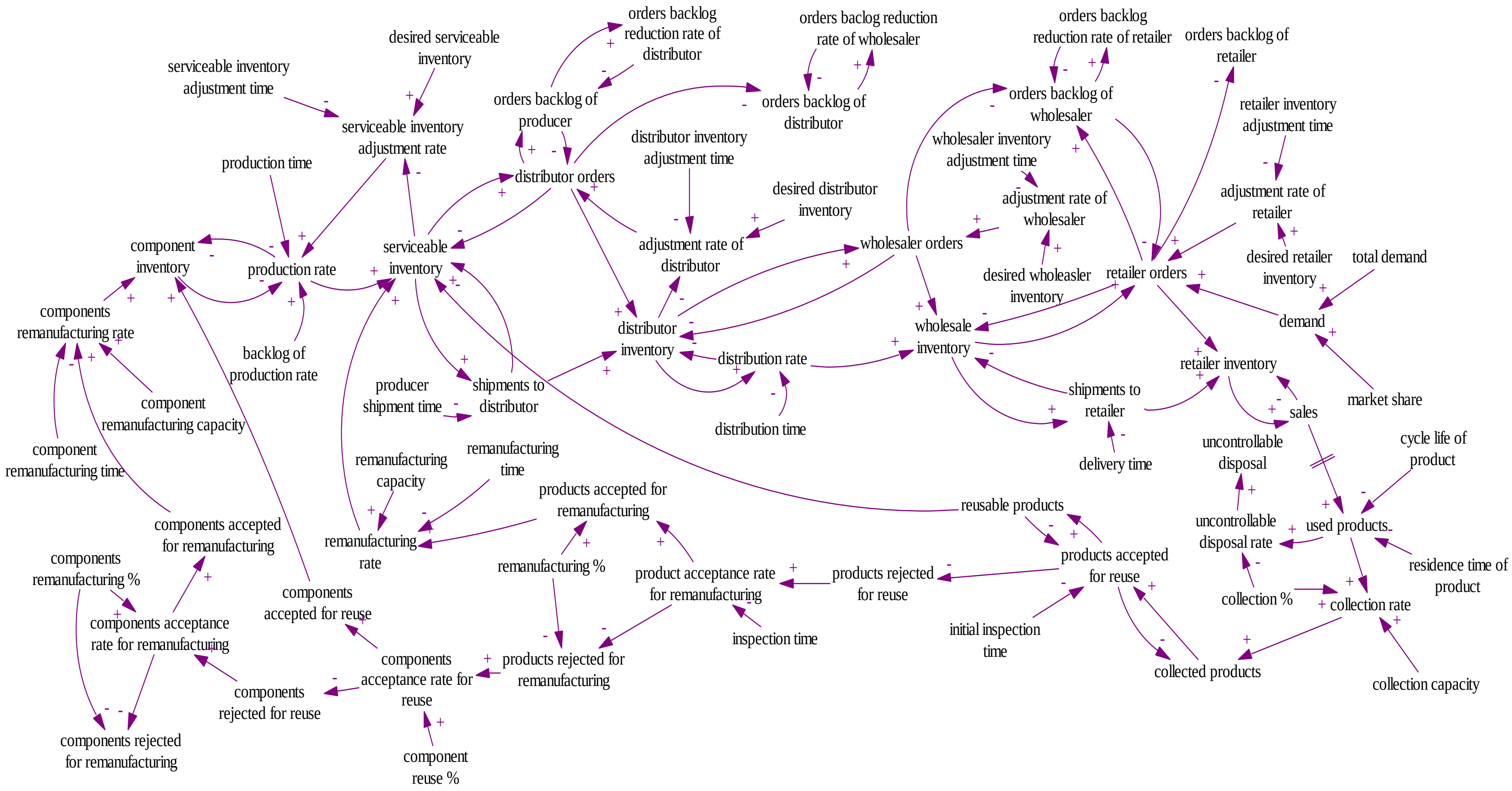


Figure 5.2: Causal loop diagram of the closed-loop supply chain

The equation simply means that the company could not produce more than its available capacity i.e. if the sum of the expected distributor's orders and the component inventory discrepancy were less than the available capacity for production of components, then the company had no need to produce more than its orders. Similarly, if there were no orders, then there was no need for production of components. However, if the sum of the inventory discrepancy and the expected orders exceeded the available capacity for the production of components, then the company had no alternative but to make components equal to their available capacity and risk getting backlogged orders. The component production capacity existed from within the system and it was determined by such factors as the speed and capacity of machines used for production and the number of workers.

The company followed a periodic review policy as described by Chopra and Meindl (2007). Under this policy, a company checks inventory at fixed regular intervals and orders when the inventory falls below a specified threshold. The time between orders was fixed but the order size in each period was not the same. The size of the order depended on the variable demand. The inventory adjustment time is described by Sterman (2000) as "the time taken to correct inventory discrepancies due to changes on demand". This is a parameter that described how responsive a supply chain is to changes in demand.

The inventory discrepancy is described as the difference between the desired threshold for the inventory and the actual inventory that the company has for that period. This value cannot be negative, hence the MAX function was used to represent the discrepancy in inventory as represented by equation 5.2.

$$inventory\ discrepancy = max(desired\ inventory - inventory, 0) \qquad (5.2)$$

It should be noted that equation 5.2 and other equations were applicable to all stages of the supply chain. The wholesale level and the retailer levels were just replicas of the distributor level with the same parameters, stocks and flows according to Sterman (2000).

Expected distributor's orders were the orders placed by the distributors as forecasted by the manufacturer. The model assumed that each level in the supply chain used the first order exponential smoothing method to forecast demand. Sterman (2000) argues that "smoothing provides a realistic model of the forecasting process used in many firms". In this case the SMOOTH function was used to model expected orders with a smoothing factor that is defined according to Mason-Jones, Naim, and Towill (1997) as described under the assumptions of the forward chain. Equation 5.3 represents the forecasting of orders by each echelon.

$$expected\ orders = SMOOTH(orders, smoothing\ factor) \qquad (5.3)$$

The production time, production capacity and the number of components per product were obtained from data provided by the company.

Once components were produced, some of them were used for the production of real products to fill the serviceable inventory. The rate at which components were used for the production of products was determined by the level of the component inventory, the time taken to make one product, the production capacity for a real product, components per product, expected orders by the distributor, the discrepancy in the serviceable inventory, and the serviceable inventory adjustment time. Once again product manufacture was limited by the capacity of the company and the rate of using components could not be below zero as that is unrealistic. The formulation in equation 5.4 used the MAX and MIN functions to define the components used for product production.

$$cpp = max\left(min\left(min\left(\frac{CI}{pt}, pc \times \frac{c}{p}\right), (EDO + \frac{SID}{SIat}) \times \frac{c}{p}\right), 0\right) \qquad (5.4)$$

Where *cpp* is the components used for product production, *CI* is the component inventory, *pt* is the product production time, *pc* is the production capacity, *SID* is the serviceable inventory discrepancy and *SIat* is the serviceable inventory adjustment time.

The components used for product production impacted the production rate as illustrated in equation 5.5.

$$production\ rate = \frac{cpp}{\frac{c}{p}} \qquad (5.5)$$

As explained, in the periodic review policy, there was a desired threshold of inventory. In this model, this was determined by the expected distributor's orders and the distributor inventory cover time as shown in equation 5.6.

$$dSI = EDO \times SIct \qquad (5.6)$$

Where *dSI* is the desired serviceable inventory and *SIct* is the serviceable inventory cover time.

Sterman (2000) describes the inventory cover time as "a level of extra stock that is maintained to mitigate risks of stock out. This was the number of weeks the supplier could ship at the current rate, given its current inventory". In other words, the inventory cover time meant the length of time that inventory would last given current usage. Each echelon in the forward chain placed an order based on their inventory discrepancy, forecast orders and inventory adjustment time. The orders placed by each echelon is a rate based on the amount of orders placed per unit time. The orders placed by each echelon to the preceding one are explained by equation 5.7.

$$distributor\ orders = EWO + \frac{DID}{DIat} \qquad (5.7)$$

Where *DID* is the distributor inventory discrepancy and *DIat* is the distributor inventory adjustment time. Every order placed by each downstream echelon was fulfilled by shipments made to that echelon by the preceding echelon. In this case, shipments could fulfil both the orders and cover existing backlogs or could fail to cover everything leading to the accumulation of backlogged orders. Shipments to an echelon were a function of available inventory, backlogged orders and the shipment time. The company shipped according to its capacity in that period. Because of the capacity limitations, the IF ELSE statement was used in equation 5.8 to indicate shipments made by an echelon.

$$shipments\ to\ distributor = \frac{(IF(DI - WBO \geq 0)THEN(WBO)ELSE(DI))}{dt} \quad (5.8)$$

Where *DI* is the distributor's inventory, *WBO* is the wholesaler's orders backlog and *dt* is the distributor's shipment time. The rate at which an echelon reduced its backlogs was equated to the shipment rate.

The eight equations summarised in the above paragraphs represented the forward chain as generated from the manufacturing echelon. The stock and flow diagram of this model is shown in Figure 5.3.

The main assumptions in the forward chain are the following:

- The supply chain was serial with three echelons (i.e. the customers are not considered as an echelon), each echelon has one predecessor and one successor.
- Only one product was considered in each organisation under investigation.
- All players in the supply chain used the exponential smoothing method as a means of forecasting demand.
- The supply chain did not consider WIP inventories.
- The assumptions for parameter setting mentioned by Mason-Jones, Naim, and Towill (1997) that the inventory adjustment time, the transit time and the smoothing constant are directly related to the process or order lead time, i.e.

$$T_i = T_w = T_p = \frac{T_a}{2} \quad (5.9)$$

Where T_i, T_w, T_p and T_a are the inventory adjustment time, transit time, order lead time and smoothing constant respectively. The smoothing constant was said to represent the time to average sales and the average age of data in the forecast and its value determines the degree of smoothing applied to the demand and it has a limit represented in equation 5.2.

$$0 \leq \frac{1}{T_a} \leq 1 \quad (5.10)$$

- The forward chain was also based on the assumptions made by Tang and Naim (2004) that the order placed by each echelon is the average forecast plus a fraction of the discrepancy between the actual and the target inventory levels.

In the stock and flow diagram for the serial forward chain, the main variables of interest included;

- Inventory adjustment time
- Inventory cover time
- Demand variance
- Demand probability distribution (this became a necessity as the case studies used had different classes of products).

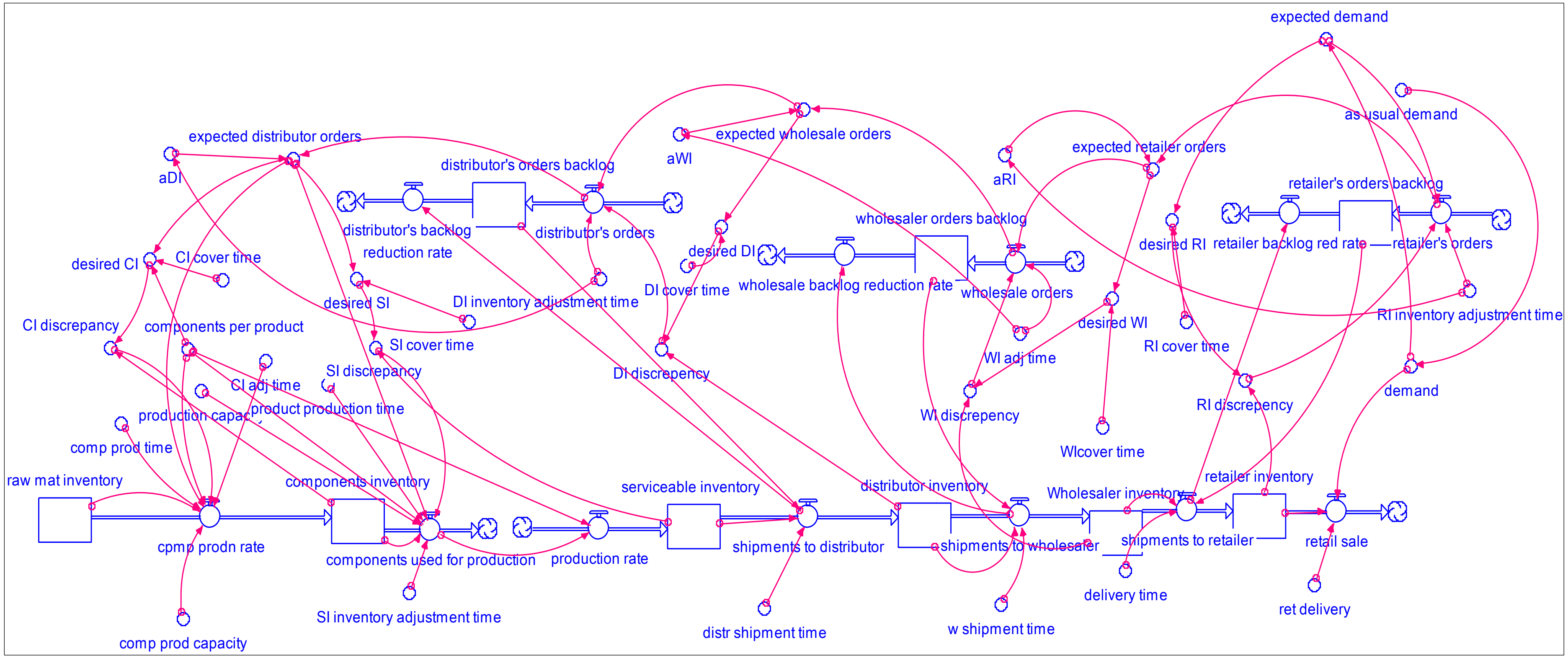


Figure 5.3: Stock and flow diagram for the serial forward chain in STELLA

The impact of these variables in the forward chain were investigated depending on the product under investigation. The forward chain as a stand-alone model was necessary for comparison purposes to see how the BWE in a supply chain changed as more and more complex structures were added to the chain. The definition of stocks, flows and auxiliary variables together with the model equations are listed in Appendix C. The verification and validation procedures carried out on this model are explained in Chapter 6.

5.2.2 Incorporating the reverse chain into the forward chain

Product returns were introduced to the forward chain. Incorporating the reverse chain introduced stocks and flows in the opposite direction from the already established forward chain. A subsystem diagram drawn from STELLA shows these stocks and flows only without some elements of the forward chain as illustrated in Figure 5.4.

The collection of used products began with retail sales. Customers keep products for a period of time, the 'residence time', before deciding to return them. Returned products defined the available used products. The available used products was a variable defined using the delay function as indicated in equation 5.11.

$$available\ used\ products = DELAY(retail\ sales, residence\ time) \quad (5.11)$$

Since it was assumed that the manufacturer managed to collect all the used products, the used product collection rate was limited by the collection capacity and the available used products as indicated in equation 5.12.

$$collection\ rate = MIN(collection\ capa\ city, available\ used\ products) \quad (5.12)$$

In this case, if there were more available used products than can be collected, then it meant that they were carried over to the next period and a backlog of collected products was developed. A parameter called 'uncollected products' was introduced to modify equation 5.12. Uncollected products is represented using equation 5.13.

$$uncollected\ products = MAX(available\ used\ products - collection\ capacity, 0) \quad (5.13)$$

The equation meant that if there were more products than could be collected then they were stored as uncollected products. These uncollected products were added to the available used products for collection in the next period and equation 5.12 was modified to 5.14.

$$colle\ rate = MIN(colle\ capacity, available\ used\ products + uncollect\ products) \quad (5.14)$$

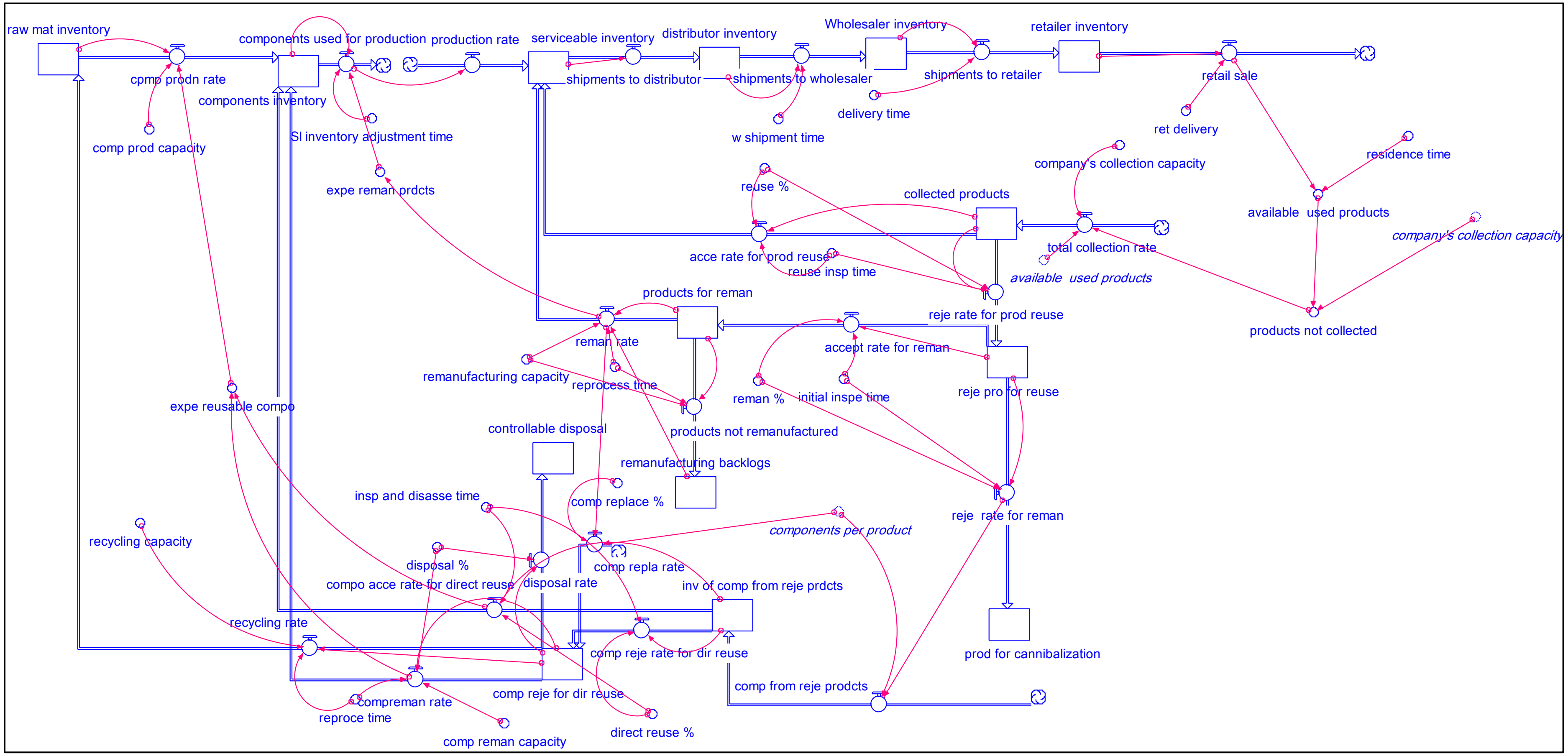


Figure 5.4: Stock and flow diagram for the reverse chain without some components of the forward chain in STELLA

Equation 5.14 ensured that all uncollected products were carried over to the next period and that the company did not collect products beyond their collection capacity limits. Products collected were inspected and determined if they were suitable for remanufacturing. This inspection brought about the product acceptance rate for remanufacturing and product rejection rate for remanufacturing flows. These flows fed into the products for remanufacturing and products for cannibalisation respectively. The product acceptance rate for remanufacturing is represented in equation 5.15.

$$product\ accept\ rate\ for\ remanufacture = \frac{(remanufacturing\ percent \times collected\ products)}{initial\ inspection\ time} \quad (5.15)$$

Similarly, the rejection rate for remanufacturing is represented in equation 5.16.

$$rejection\ rate\ for\ remanufacture = \frac{((1-remanufacturing\ percent) \times collected\ products)}{initial\ inspection\ time} \quad (5.16)$$

The rate at which products were remanufactured was limited by the company's remanufacturing capacity, the products for remanufacturing and the remanufacturing time. In the presence of remanufacturing capacity limits, backlogs of products to be remanufactured were created in an instance where the products for remanufacturing were more than the remanufacturing capacity of the organisation.

A flow known as 'products not remanufactured' was introduced to feed into remanufacturing backlogs stock. The equation for this flow was as follows:

$$products\ not\ remanufactured = MAX\left(\left(\frac{pr}{rt}\right) - rc, 0\right) \quad (5.17)$$

Where *pr* is the product for remanufacturing inventory, *rt* is the reprocessing time and *rc* is the remanufacturing capacity

In the event that 5.17 returned a value greater than zero, then there were some backlogged products for remanufacturing and these had an impact on the remanufacturing rate to produce equation 5.18.

$$rr = IF\left(\left(\frac{(pr+rb)}{rt}\right) \geq rc\right) THEN(rc) ELSE(0) \quad (5.18)$$

Where *rb* are the remanufacturing backlogs and *rr* is the remanufacturing rate.

As explained before, the assumption was that a company strictly followed its upper and lower bounds on capacity. This meant that whenever they managed to collect products below their remanufacturing capacity, they stored them as backlogs until they collected enough products for remanufacturing, so there was no remanufacturing for that period and the remanufacturing line had some downtime. Similarly, when the company collected more than the remanufacturing capacity, they only remanufactured what their capacity allowed in that period and stored the extra as backlogs to be added to the next period's collected products. These two scenarios were described by Heydari, Govindan, and Sadeghi (2018).

The remanufacturing of products introduced the expected remanufactured products, which had to be forecast by the company. These were necessary as they affected the components used for product production. Products remanufactured added to the serviceable inventory in the forward chain which meant that the company had to manufacture less products. The expected remanufactured products were represented by equation 5.19.

$$ERM = SMOOTH(rr, 1) \tag{5.19}$$

Where ERM are the expected remanufactured products.

The equation for components used for product production, 5.4 was also modified to accommodate the reverse chain as follows;

$$cpp = max\left(min\left(min\left(\frac{CI}{pt}, pc \times \frac{c}{p}\right), \left(EDO - ERM + \frac{SID}{SIat}\right) \times \frac{c}{p}\right), 0\right) \tag{5.20}$$

When products were rejected for remanufacturing they were fed into the inventory of products rejected for remanufacturing to be cannibalised i.e. to be torn down to recover useful components. Components recovered from cannibalised products were either remanufactured, reused directly or recycled (material recovery). Recycling was not looked into in this dissertation. The 20 equations listed in the document gave a brief summary of what happened in both the forward and reverse chain. All the equations in the model are listed in Appendix D.

With the incorporation of product returns, the main factors of interest in the forward chain got an addition of other factors of interest such as;

- Residence time (the time that a consumer keeps the product before deciding to give it up for collection)
- The remanufacturing capacity
- Reprocessing time
- Remanufacturing percentage (the percentage of the successfully collected products that can be successfully remanufactured.)

These factors were common for Scenarios 2 through 5 described in Chapter 4. All stocks, flows, auxiliary variables can be found under Appendix B and the model equations can be found under Appendix D.

5.2.3 Model testing

The terms 'verification' and 'validation' are sometimes used interchangeably and they are said to mean the same thing. However, some authors emphasise that there is a difference between verification and validation in the context of simulation modelling. Hillston (2003) showed a clear distinction between verification and validation. Verification makes sure that the model performs its intended task. Validation is used to demonstrate that the model behaves like or mimics the real case study that it is intended to represent. The authors claim that, whereas model verification techniques are general, the approach taken to model validation is usually much more specific to the model and the system in question.

Model verification

The following tests as listed by Hillston (2003) were used in verifying the forward chain of the model.

The use of a deterministic model

Using a deterministic model helped the modeller to see whether the model was behaving correctly. For the model of the serial chain, the demand was tested using a constant demand of 400 units per week. This was a simple stable, constant and deterministic demand and no random variables are present. Under normal conditions, a constant demand would mean constant order levels for the retailer, distributor and the wholesaler. This was the first test of the model. The graphs were plotted whilst running the simulation and the picture is a direct output from STELLA. Using the constant demand, Figure 5.5 shows the graphs for the retailer's, distributor's and wholesaler's orders.

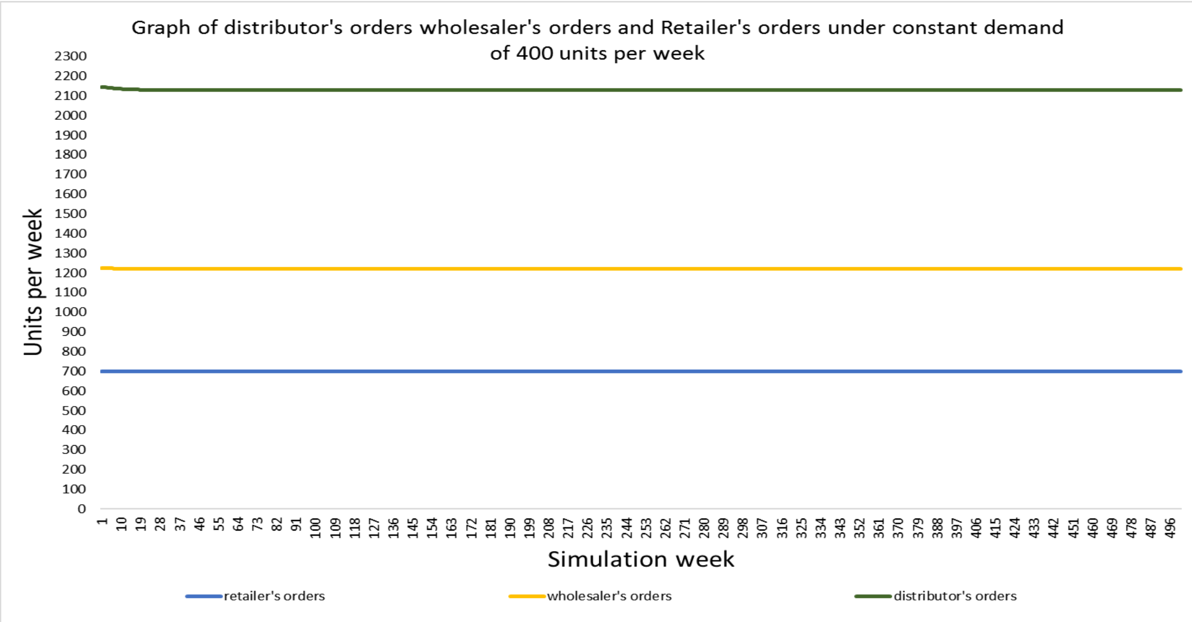


Figure 5.5: Distributor, wholesaler and retailer orders under constant demand

For all of the models, a stable demand means stable inventory levels. It became easier to forecast demand as well as expected returns. When the demand became constant, the inventories for product returns also became constant. Figure 5.6 shows graphs for inventories of returned products for a constant demand of 400 units per week.

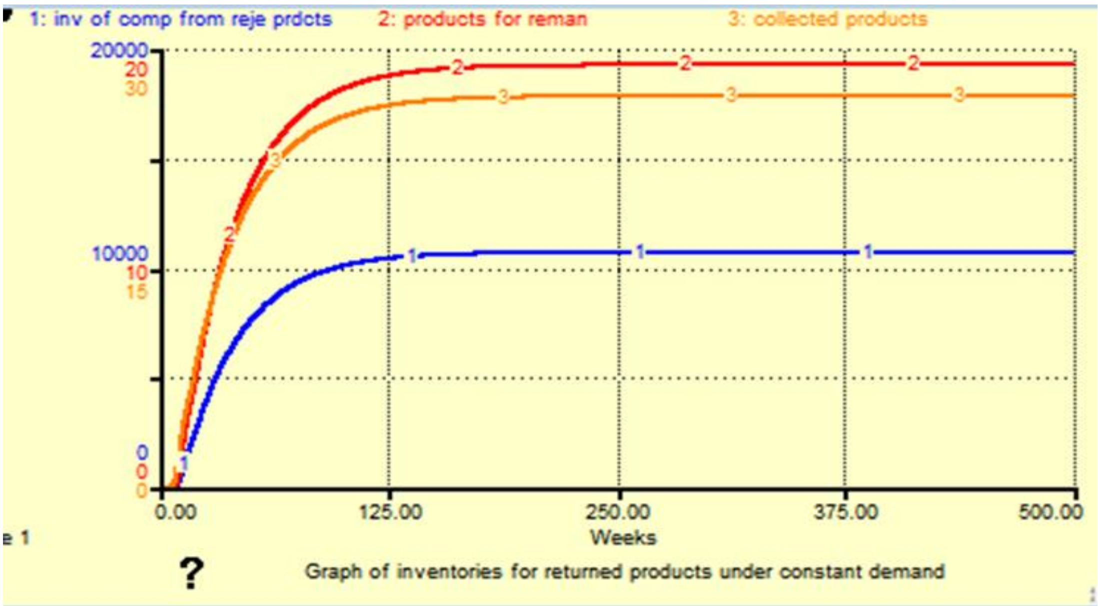


Figure 5.6: Inventory levels in the reverse chain when the demand is constant

As expected, the inventories become constant as the demand continues being constant. They only change at the beginning of the simulation run because of the initial conditions. The models therefore behaved as expected under deterministic conditions.

I. Continuity testing

Continuity testing is performed by running a simulation model several times for slightly different values of input parameters. For any one parameter, a slight change in input should generally produce only a slight change in the output. Any sudden changes in the system were an indication of an error which should be investigated unless it is a part of model behaviour.

For the forward chain, the test for continuity involved varying the values of the stable demand. In real-world systems, increasing stable demand means increasing orders though the orders will be constant throughout the periods. The graphs for different levels of stable demand should have similar shapes though the graph for demand of 600 should have more orders than the graph of demand 400 units say, but their shapes will be similar. This test was carried out for retailer's orders, wholesaler's orders and distributor's orders. Figure 5.7 shows the graph for wholesaler's orders.

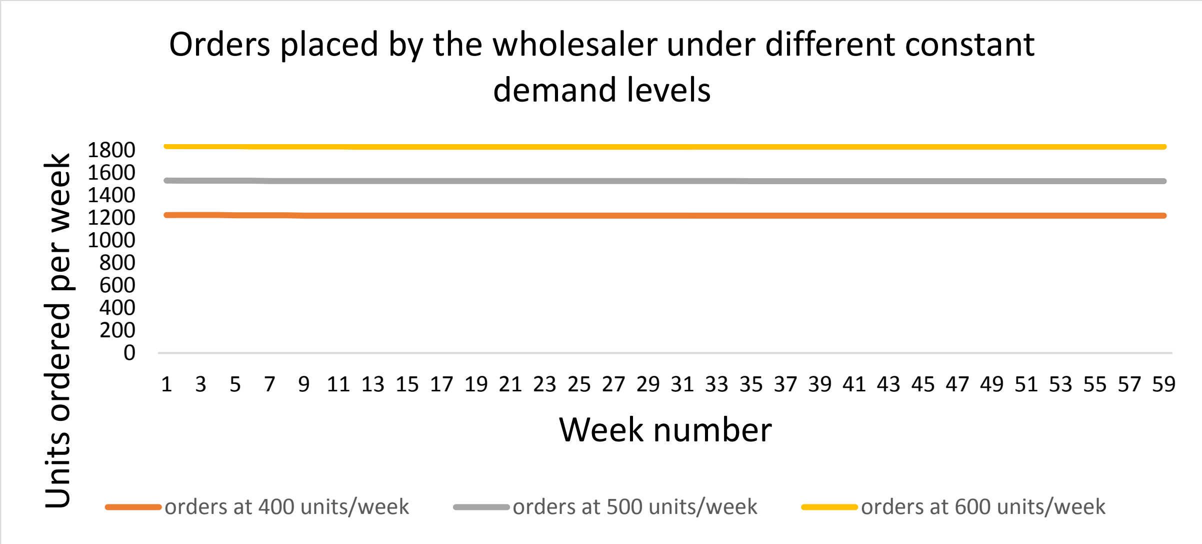


Figure 5.7: Continuity tests for wholesaler orders under different levels of constant demand

The system behaved as expected in this aspect as well.

II. Degeneracy/Extreme conditions test

Extreme conditions tests Involve inputting extreme values of parameters which were not intended for the model's input range. It helped the modeller to identify mistakes although extreme conditions do not necessarily represent typical cases.

An extreme condition test for a supply chain was when there was no demand at all for the end product. Under normal conditions, when there is no demand, production stops because no one would continue manufacturing a product for which there is no demand. The order backlogs at all levels of the supply chain will decrease to zero as there will be no more incoming orders at each level of the supply chain. Inventories at all levels should also be zero as there will be no orders to reduce inventory levels. Figure 5.8 shows these decreases under the extreme conditions of zero demand. The model behaved as expected under extreme conditions.

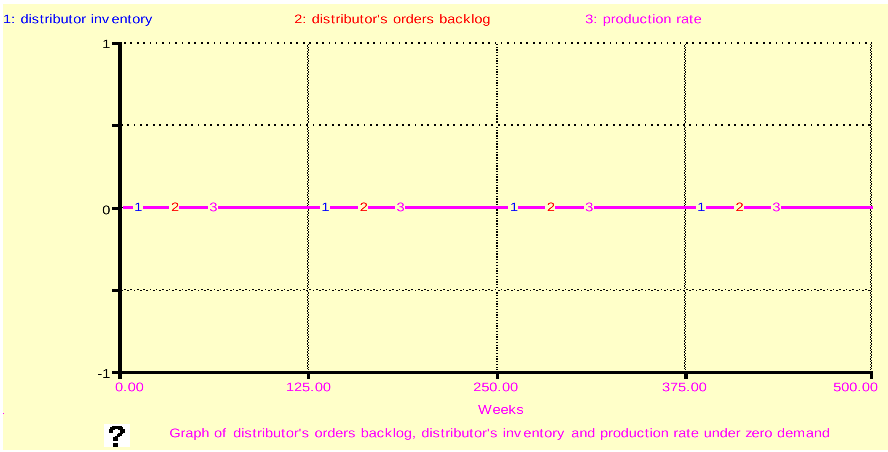


Figure 5.8: Distributor's backlog, production rate and retailer inventory under zero demand

Another example of the extreme conditions tests carried out when the production capacity was set to zero. This meant that the manufacturer failed to make products either due to a breakdown or a strike. The order backlogs at all levels should increase as there will be incoming orders which are not being satisfied. The inventories will drop to zero as there will be no supply of stock.

For the closed-loop system, setting the collection capacity to zero, meant that no products could be collected by the collector, hence there should be no reverse logistics activities. All used products after their residence period will go to the uncontrollable disposal inventory. The inventory increases sharply at the beginning of the experiment runs and with constant production, demand and residence time, the inventory becomes constant at certain levels. The collected products inventory disappeared and dropped to zero when the collector failed to collect used products. This behaviour was similar to the real-world experience which showed that the model behaved normally under extreme conditions.

In addition to verification tests listed by Hillston (2003), Forrester and Senge (1980) also list some tests used in the validation of systems dynamics models. Not all tests were listed in this dissertation but only those that were employed.

Model validation

In validating the models, two tests were used in this dissertation;

I. The dimensional consistency test

This test was used to analyse the consistency of a model's equations. Failure to pass this test by inclusion of parameters with little or no meaning as independent structural components often revealed faulty model structure. In STELLA and VENSIM, there is an option to enforce unit consistency. Once this feature was enabled, a model could not run until the units of all parts of the model were consistent. The test was important in identifying wrong equations and error in the use of units. Figure 5.9 shows a use of this feature in STELLA.

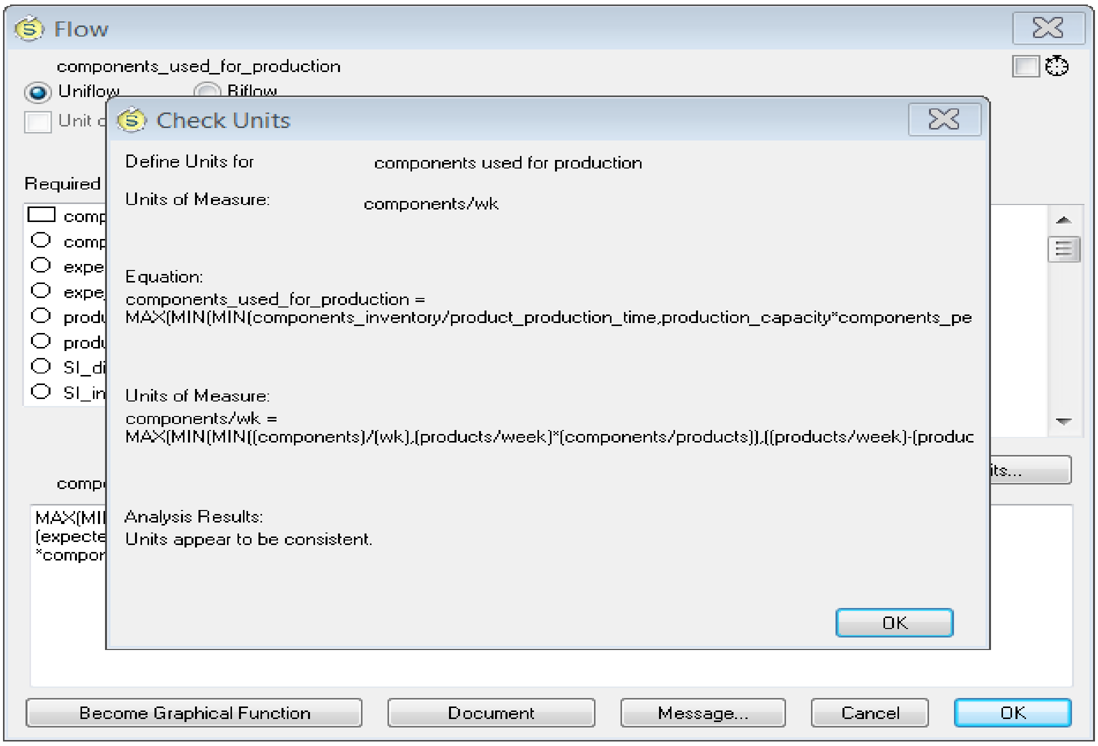


Figure 5.9: Dimensional consistency check in STELLA

II. Direct structure tests

The tests were used for assessing the validity of the model structure by comparing it directly to knowledge about the real system as explained by Barlas (1996). Vlachos, Georgiadis, and Iakovou (2007) also emphasised how behaviour validation of a model with respect to real data is important and desirable. Unfortunately, historic demand data could not be obtained from the case study companies taking part in this research, therefore, no long-term data compatible with the time horizon of this model was available.

Because of these limitations, two direct structure tests, were performed as mentioned by Barlas (1996): (1) theoretical structure tests and (2) empirical structure tests

1. Theoretical structure tests

These tests involved comparing the model with generalised knowledge about the system that exists in literature. In this dissertation, the model was compared to the models made by Das and Dutta (2013) as well as the forward chain defined by Hussain and Drake (2011). These were the two closest articles to the model in this dissertation and they used the same methodology, although in the case of Das and Dutta (2013) they used different software.

For the forward chain of this model, the assumption was an exponential smoothing of forecasts for each echelon. The model was also based on assumptions made by Tang and Naim (2004) that the order placed by each echelon is a function of the forecast plus a fraction of the discrepancy between actual and target inventory levels and a fraction of actual and target work in progress levels. This assumption was also similar to that of the original Beer Game model described by Sterman (1989). This study chose the model by Das and Dutta (2013) because it is the only other model that did not consider work in progress inventories.

The difference between this model and that of Das and Dutta (2013) is the consideration of the smoothing factor as mentioned by Mason-Jones, Naim, and Towill (1997). Mason-Jones et al. (1997) developed parameter settings for pipeline feedback that when the equations are implemented, they would result in a supply chain design that is responsive but still demonstrates low variations within each echelon. In their parameter settings, they claimed that the inventory adjustment time, transit time and the smoothing constant are directly related to the order lead time. Because of this adaptation, the model in this thesis, although it exhibited the same patterns as those of Das and Dutta (2013), had lower values of BWE. The lower values could also have been as a result of different software. Das and Dutta (2013) used VENSIM software while this dissertation uses STELLA. This difference was deemed insignificant as the models showed the same patterns when the inventory adjustment and cover times were varied.

2. Empirical structure tests

Empirical structure tests involved comparing the model structure with the information obtained directly from the real system being modelled. The models were built for more than one organisation and data for each organisation used as a case study for the research was input into the model as a way of empirically testing the model. The use of this data will also be explained in the policy and scenario experimentation in Chapter 7.

5.3 Conclusion

This chapter focused on the model design and formalisation as well as its verification. In the model design stage, the causal loop diagrams and model boundary diagram (scope) were defined. Similarly, some useful equations form both the forward chain and reverse chain were defined in the formalisation stage. The formalisation stage included developing stocks, flows and auxiliaries for the model. The models were finally verified and validated through direct structure tests and extreme condition tests among others. In Chapter 7 the validated models will be used for experimentation of different policies and scenarios using different companies and products.

CHAPTER 6
CASE STUDY SELECTION AND EXPERIMENTAL DESIGN

This chapter explains the inclusion and exclusion criteria used for selecting the case study companies used in the research. The case studies used in the research will be briefly described. Unfortunately, no company names will be mentioned in this dissertation because the organisations only agreed to participate on condition that no names would be mentioned. The chapter also explains the design of experiment methodology used. The MANOVA tests for significance and other tests that will be used to analyse the findings of the simulations are also explained.

6.1 Selecting cases

As previously mentioned, this is a comparative research, with the units of comparison being entire closed-loop supply chains. Because of this, a multiple case study with at least 2 closed-loop supply chains was a necessity and not a choice. The research however, was not limited to just two case studies, the more case studies the better the comparison. The research was also not limited to specific products as case studies. This is because of the difficulty of finding organisations operating closed-loop supply chains with remanufacturing, so various products were included depending on the case studies that the researcher managed to find.

Depending on case studies, it was necessary to compare one product per case study. If an organisation runs closed-loop systems for more than one product, then each product was treated as a case study. Most remanufacturing and reuse processes are common in automotive, mobile phone, computers, cameras, cartridges and electronic products. It is not easy to find such processes in the process industry, such as in the manufacture of plastics or products like crude oil or sugar.

In selecting cases, exclusion and inclusion criteria were used based on the research question. The main focus of the research was measuring the BWE in closed-loop supply chains. This meant that no consideration was made to open loop, open group or any other reprocessing scheme which was not a closed-loop supply chain. This was because most of these systems are just similar to extended forward chains and the BWE remains unchanged as there are no products returning to the original forward chain. The subsections that follow list the inclusion and exclusion criteria of cases.

6.1.1 Inclusion criteria

The following inclusion criteria were defined for selecting the case studies:

- Case studies suitable for this research needed to be strictly closed-loop supply chains as described by Asif (2012) and Prahinski (2006). This meant companies in which “the product returns to the OEM and that they can lead to a business to make adjustments in product design and procurement practices”. In such cases, Asif (2012) mentions that “the core is collected by the OEM or the third party remanufacturer that acts as the supplier to the OEM”. The core is supposed to enter the system and is used in the mainstream of a manufacturing forward material flow and thus impacts the forward chain activities. Under such circumstances, Prahinski (2006) mentions that “the remanufactured product is sold in the same way as the new one, i.e. the remanufactured product is not considered as a different product variant and order and supply is not handled separately". In other words, the research only focused on those cases in which the process of reverse logistics had an impact on the forward chain of the OEM and not on those supply chains where one OEM forms their supply chain at the end of another's supply chain. An example of such a case study is Fuji Xerox, where they collect their single use cameras for reuse by replacing some components and reselling them again to the same market. The camera goes back to its OEM and its original forward chain.

- Recycling companies were only considered if the OEM recovered material to make the original product from which the material comes from and the product went back to the original forward chain. An example is in the case of Armstrong tiles. The company collects used ceiling tiles from large replacement products and they grind them to recover material to make new Armstrong ceiling tiles to be sold to the same market.

6.1.2 Exclusion criteria

Similarly, the following exclusion criteria were defined for selecting the case studies:

- As explained in the inclusion criteria, open loop supply chains were not included in this research. Once again Asif (2012) stated some reasons for a supply chain not to be classified as a closed-loop supply chain. In this case, the recovered cores do not enter the main stream of the forward supply chain and the recovered contents of the original products are used by other firms to manufacture products that serve a different purpose. As an example, Apple authorises a recycler to recycle its products but Apple is not involved in the process and the products do not even go back to Apple's supply chain. These types of supply chains are excluded as case studies for this research.
- The research did not look at processing industries, that is, those industries that do not manufacture discrete products, for example steel manufacturers, where component recovery, component reuse and remanufacturing could not be performed but only recycling is possible. This was because mostly when recycling alone is possible it tended to be an open loop supply chain, but if recycling alone was possible and the supply chain can be termed 'closed loop' then it was included depending on the scarcity of case studies in this field. NIKE footwear collects used sneakers and recycles them into tracks which is a different market and product.
- The research also excluded case studies that only focused on manufacturing and commercial returns (i.e. returns due to quality and product recalls, or returnable containers and bottles).

As a result of the inclusion and exclusion criteria, two companies managed to participate in the research. Most organisations were not willing to give out their technical information. Other organisations, even though they practice reverse logistics operations, practice open group recycling or open loop systems which were not applicable to this dissertation.

6.2 Case study protocol

The case study protocol documented field activities and data to be collected from the cases. It listed the methods used in data collection and the inclusion and exclusion criteria of participants. A case study protocol also listed the unit of case study analysis, which in this case was an entire closed-loop system. In this dissertation, the case study protocol followed the structure mentioned by Rose et al.(2015). This structure was explained in Section 4.2.4 in Chapter 4.

The final case study protocol for the research is shown under Appendix B. This final case study protocol was obtained following adjustments to the initial case study protocol after the pilot study. In the pilot study, the researcher discovered that there were some missing questions or considerations so adjustments had to be made.

6.3 Determination of treatment levels

The use of simulation and the experimental method meant that there were some variables that had to be controlled for the purpose of sensitivity and 'what-if' analyses. From a review of literature, a variety of causes have been listed for the BWE in both a forward and closed-loop supply chain. In this research, the following causes were of particular interest and they were varied after carrying out experimental runs using the original data of the original system;

- The inventory adjustment time (the time taken to correct inventory discrepancies due to changes on demand).
- The inventory cover time (describes a level of extra stock that is maintained to mitigate risks of stock out. The number of weeks the supplier could ship at the current rate, given its current inventory.) It can also be described as length of time that inventory will last if current usage continues.
- Residence time (the time that a consumer keeps the product before deciding to give it up for collection).
- The collection capacity (an upper limit to the amount of used products that the company could collect per unit time).
- The remanufacturing capacity (a lower and upper limit to the amount of products the company could remanufacturer per unit time).
- Reprocessing time (the time it took for the company to remanufacture a single product).
- Remanufacturing percentage (the percentage of the successfully collected products that can be successfully remanufactured).

The levels of these factors were varied accordingly based on the base case values from the case studies. To vary these factors, they were modelled as auxiliary variables in STELLA. This made them parameters whose values could easily be changed.

6.4 Design of experiments

The dissertation focuses on the impact of changing different parameters on the BWE in a supply chain. It does not focus on specific BWE values but rather on how the BWE levels change when some parameters are changed. For this reason, a full factorial design of experiments as described by Cavazzuti (2013) was not necessary. In a full factorial experimental design, the number of experiments can be determined by equation 6.1. In equation 6.1, L is the number of factor levels whilst K is the number of factors under investigation.

$$Number\ of\ experiments = L^K \tag{6.1}$$

Equation 6.1 shows that the number of experiments increases exponentially as the number of factors and factor levels increase. Cimbala (2014) argues that if cost is not an issue and if the accuracy of the results is critical, it is necessary to use a full factorial experimental design of experiments. However, as previously mentioned, this dissertation reported the trends in changes in the BWE rather than specific values of BWE, so a full factorial experiment seemed rather costly and time-consuming.

Instead of a full factorial design of experiments, a D-Optimal design as described by Hintze (2007) was used. The author mentioned that a D-Optimal design can be used for multi-factor experiments with mixed numbers of levels and it can be used when there is a limited budget and it is difficult to use a full factorial experiment. A D-optimal design is a computer-generated design, which consists of the best subset of experiments selected from a candidate set. The candidate set is the pool of theoretically possible and practically conceivable experiments. In a d-optimal design, the experimenter specifies the number of simulations they are willing to run, the number of factors factor levels and type of factors to an algorithm. The algorithm then pulls out an even set of experimental runs from the full factorial design of experiments. In this dissertation, A D-Optimal design of experiments was generated using the cordexch algorithm in MATLAB. The cordexch function algorithm in MATLAB generates a D-Optimal design with a specified number of runs for a specific design. This meant that the experimenter had a choice to specify the number of simulation they wanted to run based on cost and time. The cordexch function in MATLAB is illustrated in equation 6.2.

$$Ddesign = cordexch(K, n,' linear',' categorical', [K_1 \dots K_M],' levels', [L_1 \dots L_M]) \qquad (6.2)$$

Ddesign is an array representing the list of experiments, the factors and factor levels. K is the number of factors under investigation where K_1 represents the first factor and so on. L is the number of factor levels where L_1 is the number of levels for factor 1 and n represents the number of runs that the experimenter decides on.

6.5 Case study descriptions

This section provides brief descriptions of the cases, including their demands, capacities and delivery times. As previously mentioned, no company names were mentioned. Companies could not share their historical demand data so assumptions were made on the demand distribution. The two case studies claimed to have a stationery demand. Table 6.1 gives a brief summary of the organisations that participated in the research.

Case Study A

The case study is a branch of a large manufacturing corporation in America that sells small appliances, personal care appliances and health and beauty products for both professionals and consumers. The main branches of this corporation include, personal care division, hair goods division, professional products division, cuisine division, waring division, packaging and appliance manufacturing. For this research, the main focus was on the remanufacturing of kitchen appliances by the corporation.

The information on this company was provided by the company's corporate remanufacturing manager. The company manufactures and remanufactures kitchen appliances such as blenders, grill pans, brewers, coffee makers and popcorn makers among other products. Information provided on the remanufacturing process has been summarised in Table 6.1. The company not only manufactures and remanufactures its own products but it also collects products from other companies and remanufactures them.

This case study was of particular interest because it represented the concepts of capacity limitations well as having more products returning to the reverse chain.

Case Study B

The company is an American energy and automotive company that specialises in electric car manufacturing. The company currently has a remanufacturing operation for powertrains, electric vehicles and batteries. The information on the remanufacturing operation was provided by a remanufacturing manager and consultant who was once the manufacturing manager for the organisation. The information focused on the remanufacturing of batteries and is also summarised in Table 6.1.

6.6 Parameter setting

Case studies used in this dissertation could not provide historical data due to company policy. Because of this, some parameters had to be modelled and assumed to be used in this model. One such parameter was the end customer demand in the forward chain. The cases only provided an average of their weekly demand and it was the duty of the researcher to find an appropriate demand distribution based on product type.

Table 6.1: Information on case studies

	Company A	**Company B**
Products	Kitchen appliances	Electric vehicle batteries
Demand	4000products/week	80 products/week
Production capacity	4000 products/week	80 products/week
Components per product	15	500
Product life cycle	90 days to 3 years	8years returned after 1 to 6 months
Collection capacity	50000 products/year	3900 products/year
Disposition methods	remanufacturing	remanufacturing
Inspection time	3 to 7 minutes	2 hours
Remanufacturing capacity	6000 products/week	75 products/week
Percentage remanufactured	50-70	90
Percentage reuse	90	N/A
Disposition time	0.01 hours	12 hours

Ramaekers and Janssens (2008) mentioned that most textbooks assumed that demand is continuous and follows a normal distribution. However, the same authors mention a problem of the Normal distribution as that of producing negative demands randomly. Cobb (2016) also agreed that the Normal distribution is used because it is convenient for mathematical purposes but in actual practice, demand from customers for some products is better modelled using the Log Normal distribution. Concerning the same issue, Miles (2013) also argued that using the Normal Distribution to model supply chain tended to overcompensate with inventory and capacity buffers.

All these arguments did not necessarily mean that the Normal distribution cannot be used in modelling demand since Silver and Peterson(1985) argued that the Normal distribution can be appropriate for fast moving consumer goods and a demand during lead time greater than 10 units. In this dissertation, for the forward chain, the Normal Distribution was also modelled in order to determine if the demand distribution had any impact on the results.

The use of other distributions such as the Log Normal and the Poisson distribution depended on the type of product and the mean of the demand. For the two case studies used in the dissertation, one focused on fast moving items in the form of home appliances whilst the other had low volume and slow moving electric vehicle batteries. This meant that they could not be modelled using the same demand distribution.

Silver and Peterson (1985) mentioned that the Poisson distribution has been found to be useful for low demand items. For this reason, it was used in the dissertation for modelling the demand distribution for the electric vehicle batteries. The demand for the kitchen appliances was considered to be fast moving and was modelled using a Log Normal distribution.

6.7 Statistical analysis of simulation results

In analysing the results from the simulations, Minitab 16 Statistical Software was used for determining the main and interactive effects of the factors under investigation on the BWE in a supply chain. The main tests and what they mean are explained in Sections 6.7.1 and 6.7.2.

In carrying out the statistical analysis, a general MANOVA test was carried out in Minitab. MANOVA was used because the tests were checking the impact of factors on multiple responses that is, BWE at the retailer, wholesaler and the distributor levels. In addition, the Minitab blog (2014) listed the benefits of MANOVA over ANOVA;

- **Increased power**: If the response variables are correlated, MANOVA can detect differences too small to be detected through individual ANOVAs.
- **Detects multivariate response patterns**: The factors may influence the relationship between responses rather than affecting a single response. These types of relationships are often missed by single ANOVAs.
- **Controls the family error rate**: Chances of incorrectly rejecting the null hypothesis increase with each successive ANOVA. Running one MANOVA to test all response variables simultaneously keeps the family error rate equal to your alpha level.

A significance level of 0.05 was used because it is the most commonly used in most statistical analyses and most software assume this level of significance.

6.7.1 Tests for main effects of the factors

In determining the main effects of the factors, the test for equality of means (also known as the significance test), the test for difference between group means and the correlation test will be used. These tests determine if the impact of a factor on the dependant variable is significant and should be considered.

1. Testing the equality of means from all the responses

The test for the equality of means compares the p-values in the MANOVA test tables for each term to the significance level. In this instance, a significance level (denoted as αor alpha) of 0.05 was employed. A significance level of 0.05 indicates a 5% risk of concluding that an association exists when there is no actual association. The results from the test for the equality of means are interpreted as listed;

- P-value ≤α The differences between the means are statistically significant. If the p-value is less than or equal to the significance level, then the differences between the means are statistically significant. If a main effect is significant, the level means for the factor are significantly different from each other across all responses in the model.
- P-value > α The differences between the means are not statistically significant. If the p-value is greater than the significance level, one cannot conclude that the differences between the means are statistically significant.

2. Assessing the differences between group means

The means table is used to understand the statistically significant differences between the factor levels. The mean of each group provides an estimate of each population mean. Differences between group means for terms that are statistically significant indicate a pattern showing how a response is being affected by a factor for example if a BWE retailer increases or decreases with an increase in inventory cover time.

Besides assessing group means, the same effect will be investigated using the main effects plot. The main effects plot displays the means for each group within a categorical variable. Minitab creates the main effects plot by plotting the means for each value of a categorical variable. A line connects the points for each variable. The line is used to determine whether a main effect is present for a categorical variable.

- When the line is horizontal (parallel to the x-axis), there is no main effect present. The response mean is the same across all factor levels.
- When the line is not horizontal, there is a main effect present. The response mean is not the same across all factor levels. The steeper the slope of the line, the greater the magnitude of the main effect.

Figure 6.1 shows an example of these main effects plot as obtained from Minitab.

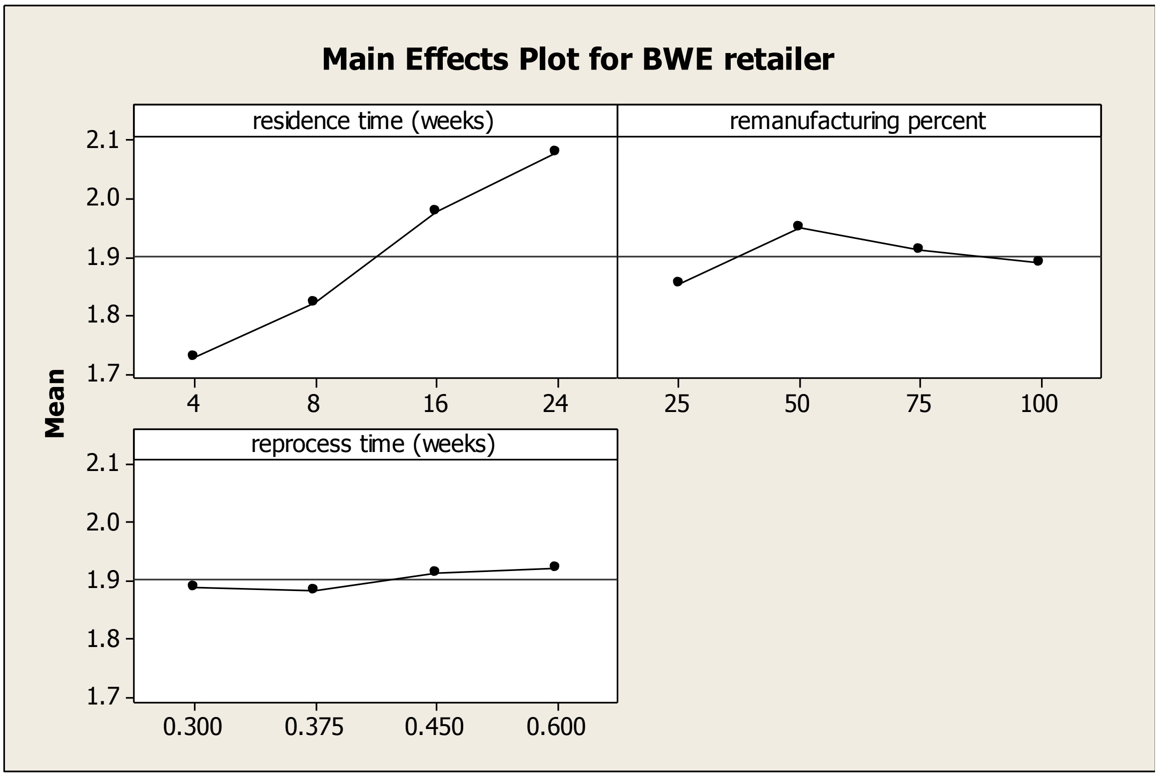


Figure 6.1: Main effects plot example

From the main effects plot in Figure 6.1, the residence time has a line with a very large slope and the values of the BWE retailer increase as the residence time increases. The line for the reprocess time is almost parallel. This means that the reprocess time had no significant impact on the BWE retailer. The line for the remanufacturing percent, although not parallel, had no defined pattern. This means that in this case although the remanufacturing percent impacted the BWE retailer, its specific impact could not be clearly defined.

3. Correlation test

According to Minitab Blog (2019), the Pearson correlation coefficient is used to examine the strength and direction of the linear relationship between two continuous variables.

a. Strength

The correlation coefficient ranges in from −1 to +1. The larger the absolute value of the coefficient, the stronger the relationship between the variables.

b. Direction

The sign of the coefficient indicates the direction of the relationship. If both variables tend to increase or decrease together, the coefficient is positive. If one variable tends to increase as the other decreases, the coefficient is negative.

c. Significance

Minitab also outputs the correlation results best on their significance. If the p-value is less than or equal to 0.05, then correlation is significant. If p-value is greater than 0.05, then correlation is insignificant.

6.7.2 Test for interactive effects of the factors

The test for interaction was carried out using the significance of correlation between each of the factors. An insignificant correlation meant no interaction between factors and vice versa.

6.8 Conclusion

This chapter served to introduce the reader to the main case studies used in the research. By explaining the inclusion and exclusion criteria used in selecting case studies, the chapter defined the scope of the research. The chapter also explained the experimental design used to determine the number of simulation runs for each scenario. In addition to the design of experiments, the chapter aimed at helping the reader to understand the statistical analyses of experimental results as they will be carried out in Minitab 16 software in Chapter 7 of the dissertation. Chapter 7 will explain the experimental plan and carry out the policy and scenario experimentation of this research.

CHAPTER 7
CASE STUDY AND SCENARIO EXPERIMENTATION

This chapter describes the scenario experiments. The chapter begins by describing the experimental plan. The rest of the sections follow this plan and describe the results as the plan proceeds. The chapter also describes the Minitab outputs for the tests for the various experiments. All these experiments are based on the two case studies identified in Chapter 6.

7.1 Experimental plan

Chapter 5 mentioned that the research focused on both the forward and the reverse chains. Before identifying the factors of the reverse chain that had an impact on the BWE, it was necessary to first study the forward chain without any product returns. This is done for comparison purposes so that one can tell the impact of the reverse chain on the BWE in a supply chain. Section 7.2 will look at forward chain experiments while Sections 7.3, 7.4, 7.5 and 7.6 will mostly focus on the different scenarios of the reverse chain. This flow of experiments based on sections is shown in the tree diagram in Figure 7.1. Each section will also have a tree diagram to show how the experiments for that section were executed.

The BWE was measured for three levels/echelons in the supply chain, the distributor level, wholesaler level and the retailer level. From this point forward, these three measurements will be represented as the BWE distributor, BWE wholesaler and BWE retailer. The BWE was measured using the variance ratio as defined by El-Beheiry et al. (2004). The ratio was given as:

$$Bullwhip = \frac{var(q)}{var(d)} \qquad (7.1)$$

Where *var (q)* is the variance of orders placed by ab echelon and *var (d)* is the variance of the demand. The BWE is a ratio with no units. A ratio above 1 indicates the presence of the BWE in the system.

Experiments for the forward chain with no returns were important in this dissertation for two reasons:

- For comparison purposes, i.e. to see how the BWE changes with the introduction of the reverse chain.
- They also served for validation purposes. The forward chain investigated factors that were similar to those of Das and Dutta (2013). Chapter 5 mentions the models developed by Das and Dutta (2013) as one of those used for validation purposes.

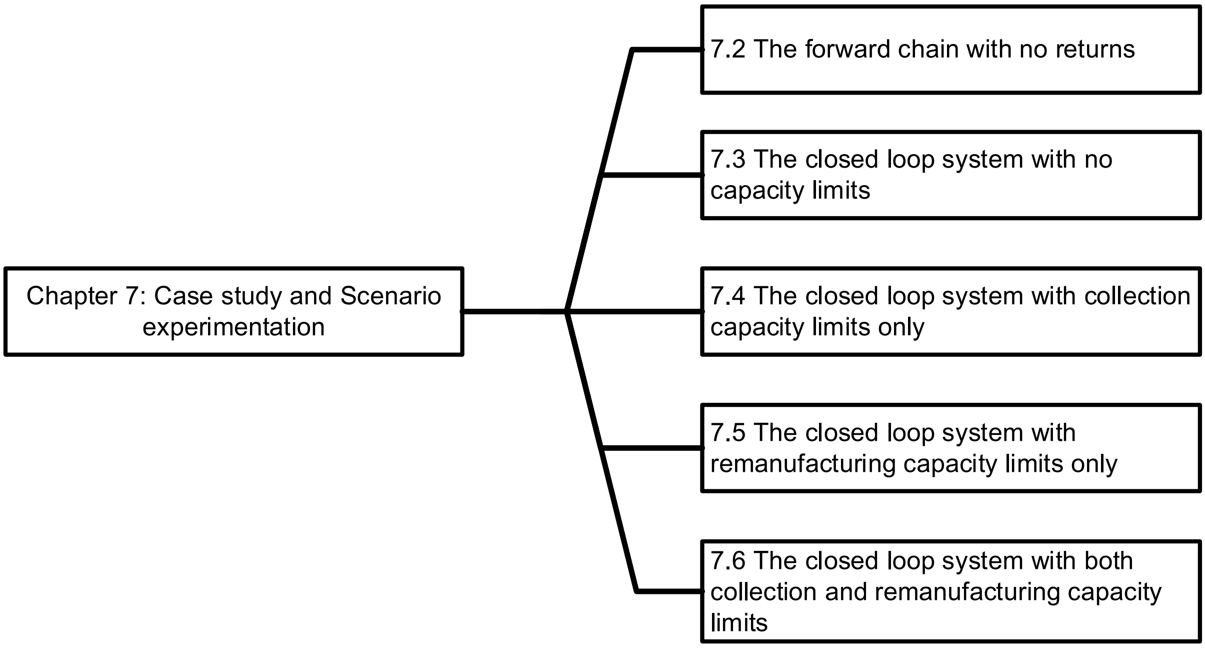


Figure 7.1: Flow of experiments based on subsections

7.2 The forward chain with no returns

In this section again, the flow of experiments is represented by a tree diagram. From the tree diagram in Figure 7.2, two products will be investigated for the forward chain, the electric vehicle batteries (slow moving items) and the kitchen appliances (fast moving consumer items). The electric vehicle batteries were first modelled with a normally distributed demand then with a Poisson demand distribution. Similarly, the kitchen appliances were first modelled with a normal demand distribution then with a lognormal demand distribution. Three measurements were considered, the BWE distributor, BWE wholesaler and the BWE retailer. The parameters under investigation in the forward chain are shown in Table 7.1.

Table 7.1: Parameters in the forward chain

Parameter	Value for case A	Value for case B
Fixed Parameters		
As Usual Demand	Log Normal (4000)	Poisson(80)
Components per product	15	500
Production capacity	4000 products/week	80 products/week
Delivery time	1 week	1 week
Product production time	1/4000 weeks	1/80 weeks
Component production time	1/(4000*15) weeks	1/(80*500) weeks
Component production capacity	(4000*15) components/week	(80*500) components per week
Variable parameters under investigation		
Demand variance (products/week)	2000	N/A
Distributor inventory cover time (weeks)	2,4,6,8,10	2,4,6,8,10
Distributor inventory adjustment time (weeks)	2,4,6,8,10	2,4,6,8,10
Wholesale inventory cover time (weeks)	2,4,6,8,10	2,4,6,8,10
Wholesale inventory adjustment time (weeks)	2,4,6,8,10	2,4,6,8,10
Retailer inventory cover time (weeks)	2,4,6,8,10	2,4,6,8,10
Retailer inventory adjustment time (weeks)	2,4,6,8,10	2,4,6,8,10

Using the *cordexch* function in MATLAB defined in Chapter 6, 1 000 simulations, each with 500 weeks were run for each instance of the forward chain.

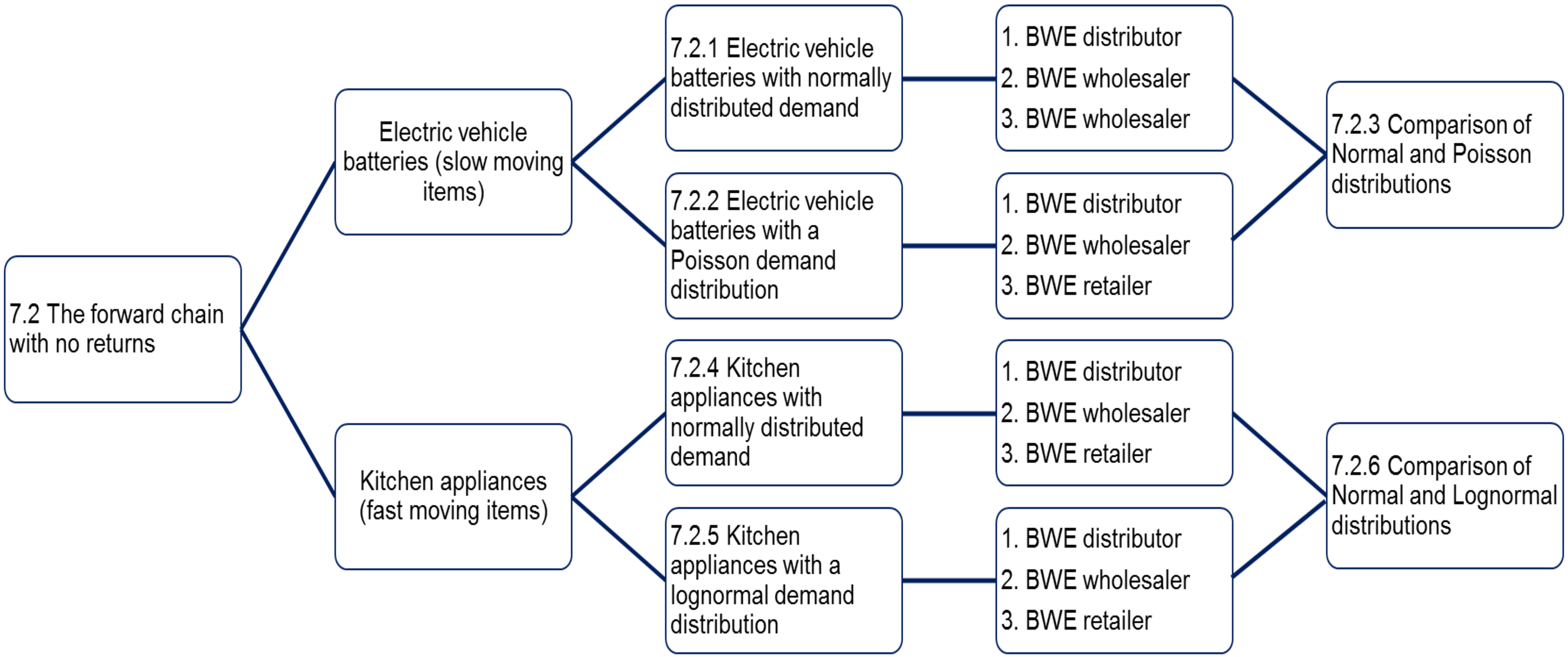


Figure 7.2: Experiment plan for the forward chain without product returns

7.2.1 Experimental results for electric batteries with a normally distributed demand pattern

BWE distributor

The experiments investigated the impact of the distributor inventory adjustment time, distributor inventory cover time, wholesaler inventory adjustment time, wholesaler inventory cover time, retailer inventory adjustment time and the retailer inventory cover time on the BWE at the distributor, wholesaler and retailer levels. Table 7.2 shows the significance test results obtained from Minitab.

Table 7.2: Analysis of variance for BWE distributor, using adjusted SS for tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DI adjustment time	4	11341001	9963990	2490998	8.93	0.000
DI cover time	4	5159044	5275294	1318823	4.73	0.001
WI adjustment time	4	16604642	16357454	4089363	14.66	0.000
WI cover time	4	4063637	4519464	1129866	4.05	0.003
RI adjustment time	4	21292979	20938467	5234617	18.76	0.000
RI cover time	4	2018576	2018576	504644	1.81	0.125
Error	1179	328954713	328954713	279012		
Total	1203	389434592				

From Table 7.2, with the exception of the retailer inventory cover time, all factors had p values less than 0.05. This meant that at the 95 percent level of confidence, all these factors were significant. Hence the BWE at the distributor level was significantly affected by the distributor inventory adjustment time, distributor inventory cover time, wholesaler inventory adjustment time, wholesaler inventory cover time and the retailer inventory adjustment time.

Table 7.3 shows a Minitab output of the least square means table. This table shows the differences between means for the BWE at the distributor, wholesaler and the retailer levels.

Looking at the least square means table, an increase in the distributor inventory adjustment time led to a decrease in the BWE at the distributor level. This was because the distributor inventory adjustment time had an impact on the smoothing factor. The smoothing factor represented the average age of data in the forecast and its value determined the degree of smoothing applied to the demand. An inventory adjustment time of 2 meant a smoothing factor of 4. A higher smoothing constant meant placing more weight on the most recent forecast for demand and hence more accurate demand forecast. This helped to reduce the BWE at the distributor level.

The BWE distributor increased with an increase in inventory cover time at that level. Similar patterns applied for the wholesaler inventory adjustment cover time and inventory cover time. This was because the orders placed by the distributor were affected by the orders and forecast made by the wholesaler and the retailer. The retailer cover time showed no pattern with the

BWE at the distributor level because it had no significant impact on the BWE at the distributor as explained by the test on the significance of factors.

Table 7.3: Least square means table for electric vehicle batteries under a normally distributed demand for the forward chain with no product returns

	BWE distributor		BWE wholesaler		BWE retailer	
DI adjustment time	Mean	SE Mean	Mean	SE Mean	Mean	SE Mean
1	289.186	34.079	23.039	4.502	12.374	4.366
2	129.591	33.671	16.874	3.840	4.314	4.448
3	59.694	34.555	13.818	4.565	3.253	4.427
4	58.638	34.295	15.293	4.531	3.511	4.394
5	45.361	34.481	18.096	4.555	2.898	4.418
DI cover time						
1	51.070	34.517	19.821	4.560	3.419	4.422
2	64.920	33.870	18.250	4.475	12.047	4.340
3	82.341	33.172	14.191	4.382	3.393	4.250
4	157.027	35.586	15.193	4.701	3.559	4.559
5	227.111	33.911	19.665	4.480	3.458	4.345
WI adjustment time						
1	348.645	33.967	49.747	4.487	12.090	4.352
2	69.999	33.924	11.317	4.482	3.328	4.346
3	58.631	34.539	9.891	4.563	3.447	4.425
4	61.106	35.733	9.456	4.721	3.424	4.578
5	44.088	32.986	6.709	4.358	3.586	4.226
WI cover time						
1	39.765	33.828	5.289	4.469	3.036	4.334
2	70.362	34.173	9.709	4.515	3.318	4.378
3	100.465	34.191	17.204	4.517	12.435	4.381
4	160.482	33.655	27.565	4.446	3.404	4.312
5	211.395	35.140	27.353	4.642	3.682	4.502
RI adjustment time						
1	383.183	35.907	60.210	4.744	20.123	4.601
2	107.048	35.003	13.811	2.908	4.624	4.485
3	43.347	33.439	6.917	4.418	1.346	4.284
4	35.739	32.900	4.648	4.346	0.933	4.215
5	13.152	34.121	1.534	4.508	0.566	4.372
RI cover time						
1	51.759	34.235	6.554	4.523	2.310	4.386
2	108.557	33.361	14.742	4.407	2.198	4.274
3	117.052	33.546	19.941	4.432	12.142	4.298
4	125.812	36.781	18.465	4.859	4.559	4.713
5	179.288	33.436	27.418	4.417	4.666	4.284

The table for correlation from Minitab showed the Pearson correlation coefficient in the first row and the significance of correlation in the second row. A value for significance greater than 0.05 indicated an insignificant correlation. This table as obtained from the Minitab output is represented by Table 7.4.

From the correlation table, the BWE distributor had a significant negative correlation with the distributor inventory adjustment time, wholesaler inventory adjustment time and retailer inventory adjustment time. This meant that the BWE distributor decreased significantly as these factors increased. This agreed with the findings of the two previous tests. Similarly, the BWE distributor had significant positive correlation with the distributor inventory cover time and the wholesaler inventory cover time. It increased as these factors increased. An interesting outcome of the correlation test was that the BWE distributor had strong and significant positive correlations with the BWE retailer and the BWE wholesaler. This increased as the BWE wholesaler and BWE retailer also increased. This agreed with the idea of bullwhip increasing as one moves upstream and further away from the demand.

The correlation table also outputs relationships between the factors under investigation. A significant correlation means interaction of factors. From the table, all the correlations between the demand variance, distributor inventory adjustment time, distributor cover time, wholesaler inventory adjustment time, wholesaler cover time, retailer inventory adjustment time and retailer cover time, were found to have a p-value greater than 0.05. This meant that any correlation between them was found to be insignificant, hence there was no interaction of factors.

Table 7.4: Correlation table for electric vehicle batteries under normally distributed demand

	DI adjustment time	DI cover time	WI adjustment time	WI cover time	RI adjustment time	RI cover time	BWE distributor	BWE wholesaler
DI cover time	0.015 ***0.594***							
WI adjustment time	-0.023 ***0.418***	0.037 ***0.194***						
WI cover time	0.016 ***0.037***	0.586 ***0.197***	0.019 ***0.502***					
RI adjustment time	0.030 ***0.304***	0.010 ***0.741***	-0.020 ***0.479***	0.030 ***0.305***				
RI cover time	-0.023 ***0.420***	0.029 ***0.315***	-0.025 ***0.381***	-0.006 ***0.836***	0.003 ***0.917***			
BWE distributor	-0.138 ***0.000***	0.104 ***0.000***	-0.147 ***0.000***	0.103 ***0.000***	-0.194 ***0.000***	0.080 ***0.006***		
BWE wholesaler	-0.025 ***0.395***	-0.010 ***0.724***	-0.167 ***0.000***	0.106 ***0.000***	-0.225 ***0.000***	0.094 ***0.001***	0.689 ***0.000***	
BWE retailer	-0.043 ***0.137***	-0.023 ***0.433***	-0.040 ***0.171***	-0.000 ***0.992***	-0.081 ***0.005***	0.020 ***0.479***	0.257 ***0.000***	0.571 ***0.000***

Cell Contents: Pearson correlation
P-Value

From here on, the dissertation will not show all the tables and figures from the MANOVA. Should the reader require a specific output, they can find the rest of the tables and figures under Appendix C.

BWE wholesaler

A Minitab output shown in Table C1 showing the p-values for the factors under investigation was generated from the general MANOVA test. The p-values revealed that, the distributor inventory cover and adjustment times have no significant impact on the BWE wholesaler. The wholesaler inventory adjustment time, wholesaler inventory cover time, retailer inventory adjustment time and retailer inventory cover time had a significant impact on the BWE at the wholesale level.

The test for differences between means was done by revisiting Table 7.3 under the BWE wholesaler column. Similar to the BWE distributor, as the demand variance increased, the BWE wholesaler decreased. There was no defined pattern for the distributor inventory cover and adjustment times as they were found to be insignificant in the first test.

The BWE wholesaler decreased with an increase in wholesaler inventory adjustment time. The same variable increased with an increase in wholesaler inventory cover time. Although the test for significance indicated that the retailer inventory adjustment and cover times were significant, there was no defined pattern on the main effects of the two parameters on the BWE wholesaler.

Revisiting Table 7.4 revealed the correlations for the BWE wholesaler. The variable had significant negative correlations with the wholesale inventory adjustment time and retailer inventory adjustment time. This meant that the BWE wholesaler decreased as these factors increased. The BWE wholesaler had significant positive correlations with the wholesaler inventory cover time and the retailer inventory cover time. This meant that it increased as these parameters increased.

Similar to the BWE distributor, the correlation table revealed no significant correlations between the factors under investigation. This meant that there was no evidence at the 95% level of confidence to suggest any interaction between the parameters.

The BWE retailer

The test for significance of factors under Table C2 indicated the retailer inventory adjustment time as being the only significant factor where the BWE retailer was concerned. This might have been because the retailer was the supply chain player close to the demand and his forecasting of orders was only impacted by the smoothing factor which was affected by the inventory adjustment time.

Revisiting Table 7.2 revealed that the BWE retailer decreased with an increase in retailer inventory adjustment time. There were no noticeable patterns for the other factors as they were deemed insignificant as far as the BWE retailer was concerned.

The correlation table (Table 7.4) also showed that the BWE retailer only had a significant negative correlation with the retailer inventory adjustment time. This meant that the variable decreased as the retailer inventory adjustment time increased.

Similar to the BWE distributor and BWE wholesaler, the correlation table revealed no significant interactions between the parameters under investigation.

7.2.2 Experimental results for Poisson distribution of electric vehicle batteries

The electric vehicle batteries were also modelled using a Poisson distribution to find out the impact of the demand distribution on the BWE values.

BWE distributor

Similar to the Normal distribution of the same data, the distributor inventory adjustment time, the distributor cover time, the wholesaler inventory adjustment time, the wholesaler cover time, the retailer inventory adjustment time have significant impact on the BWE at the distributor level. The only difference is that in this instance the retailer cover also had significant impact. This was obtained from the Minitab output shown in Table 7.5.

Table 7.5: Test for significance for BWE distributor for Poisson distribution

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DI adjustment time	3	23361628	23298346	7766115	22.14	0.000
DI cover time	3	9805625	9500917	3166972	9.03	0.000
WI adjustment time	3	15312621	15358310	5119437	14.59	0.000
WI cover time	3	9373023	9314884	3104961	8.85	0.000
RI adjustment time	3	37261902	37097491	12365830	35.25	0.000
RI cover time	4	5153137	5153137	1288284	3.67	0.006
Error	880	308701774	308701774	350797		
Total	899	408969710				

Main effects plots were used to determine patterns of how the BWE distributor is impacted by the factors under investigation. Figure 7.3 shows such plots for the BWE distributor as obtained from Minitab.

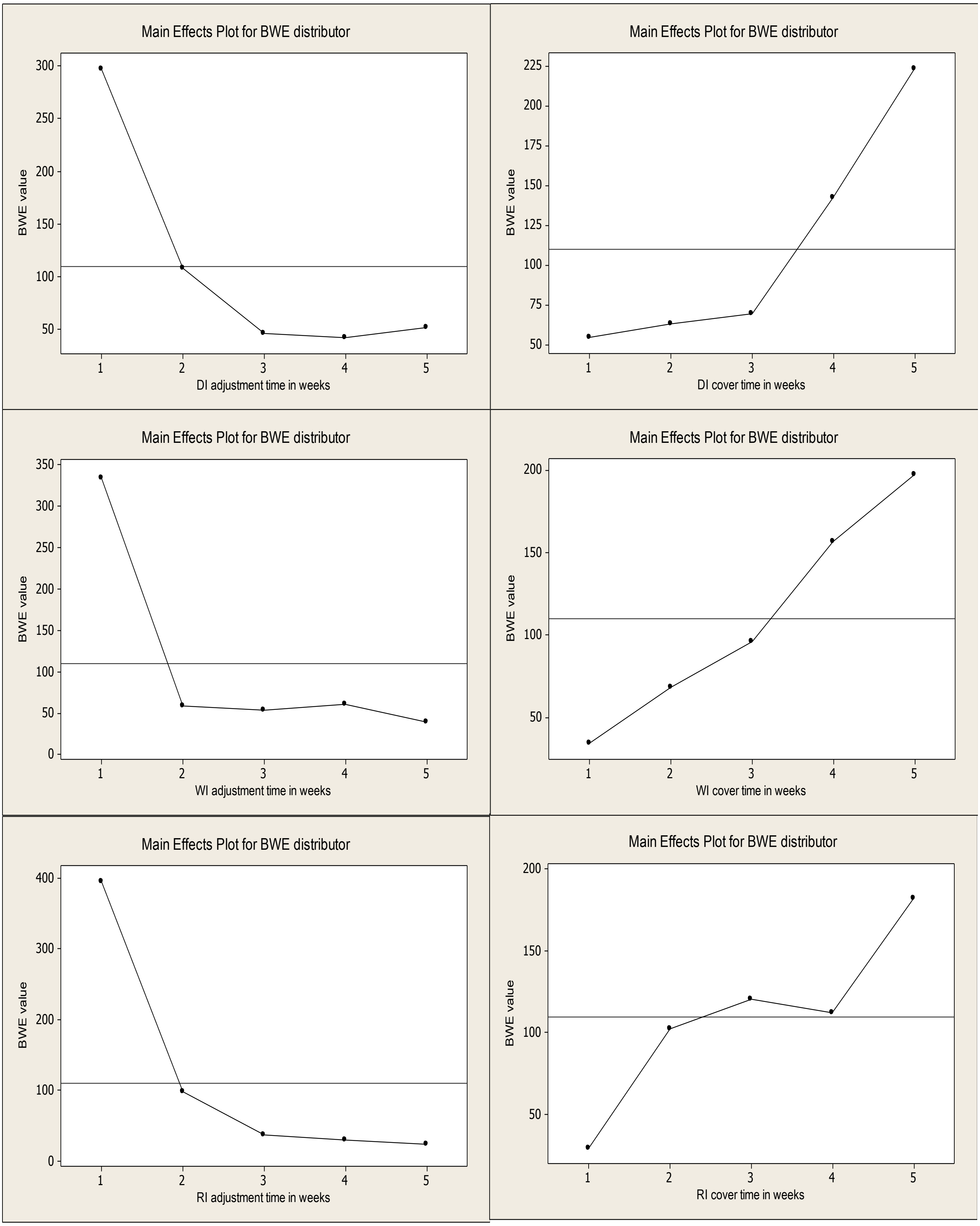


Figure 7.3: Main effects plots for BWE distributor for the Poisson distribution

From the figure, the BWE distributor decreased with the increase in inventory adjustment time, wholesaler inventory adjustment time and retailer inventory adjustment time. The BWE distributor increased with an increase in the distributor inventory adjustment time and the wholesaler inventory adjustment time. There was no clear picture as to how the BWE distributor changes with changes in the retailer cover time. This suggested that the significance of the retailer cover time could have been by chance.

The Minitab output for the tests for correlation is shown under Table C3. The BWE distributor had significant negative correlation with the distributor inventory adjustment, wholesaler inventory adjustment and the retailer inventory adjustment times. This meant that the BWE distributor decreased as these times increased. In a similar way, the BWE distributor had significant positive correlation with distributor inventory cover and wholesaler inventory cover times. The BWE distributor increased as these times increased. The positive correlation between the BWE distributor and the retailer inventory cover time in this case has a p value of 0.048 which is almost equal to 0.05. This meant that at the 95% level of confidence, the positive correlation between the retailer inventory cover time and the BWE distributor is insignificant.

The BWE distributor also had significant positive correlation with the BWE wholesaler and BWE retailer. This meant that the performance of the lower stream levels had a strong impact on the BWE distributor and the value increased as the BWE wholesaler and BWE retailer also increased.

The correlation table showed that there were no significant negative or positive correlations between the factors under investigation which meant that there was no interaction between factors.

BWE wholesaler

Table C4 (under Appendix C) shows that the distributor inventory cover time had no significant impact on the BWE wholesaler. Similarly, the value for the distributor inventory adjustment time was closer to 0.05, which meant that significance could have been by chance. The wholesale inventory adjustment, wholesale inventory cover, retailer inventory adjustment and retailer inventory cover times had significant impact on the BWE wholesaler.

The main effects plot in Figure C1 shows how the BWE wholesaler varied with the parameters under investigation for the Poisson distribution.

From the figure, the distributor inventory adjustment time had no defined pattern which meant that it had no distinguished impact on the BWE retailer. Similarly, the distributor inventory cover time had no distinguished impact and the line was almost parallel which meant that every level of this factor produced the same results for the BWE wholesaler, hence it had no impact on the BWE wholesaler.

The retailer inventory cover time also had no distinguished pattern which meant that its significance could have been by chance. The BWE wholesaler decreased with an increase in the wholesaler inventory adjustment and the retailer inventory adjustment time. The same variable increased with an increase in the wholesaler inventory cover time.

From the correlation table, Table C3, the BWE wholesaler had significant negative correlation with the wholesaler inventory adjustment and the retailer inventory adjustment times. This meant that the BWE distributor decreased as these factors increased. The BWE distributor also had significant positive correlation with the wholesale inventory cover time. The BWE wholesaler increased as the wholesaler cover time increased. The value of the p value for the positive correlation between the BWE wholesaler and the retailer inventory cover time was 0.048 which is close to 0.05. This made this positive correlation insignificant.

Again, based on the correlation table, there were no significant positive or negative correlations. This meant that there were no interactions between the factors under investigation.

BWE retailer

The test for significance of factors can be obtained under Table C5. The p-values from this output indicated that only the retailer inventory adjustment and retailer inventory cover times were significant as far as the BWE retailer was concerned

The Main effects plot indicated that the BWE retailer decreased with an increase in the retailer inventory adjustment time. The lines for the distributor inventory adjustment, distributor inventory cover, the wholesaler inventory adjustment and wholesaler inventory cover times did not have distinguishable patterns and they were almost parallel showing that the factors had no impact on the BWE retailer. The retailer inventory cover time had no distinguished pattern which meant that whatever impact it had was by chance.

From Table C3, the BWE retailer showed a significant negative correlation with the retailer inventory adjustment time and a significant positive correlation with the retailer inventory cover time. This meant that the BWE retailer decreased with an increase in the retailer inventory adjustment time and it increased with an increase in the retailer inventory cover time.

The correlation output in Table C3 also showed that there were no significant positive negative or positive correlations between factors. This meant that there were no interactions between factors under investigation.

7.2.3 Comparison between modelling the same data as a normal distribution and as a Poisson distribution

In terms of the main effects and interactive effects of the factors, the two distributions provided the same conclusions that;

- The BWE decreases with an increase in inventory adjustment time at all levels.
- The BWE increases with an increase in inventory cover time at all levels.
- The performance of the uppermost supply chain echelon is impacted by the performance of the lower supply chain levels.
- Factors in the lower echelons of the supply chain may have an impact on the BWE of the upper levels but factors in the upper levels do not have any impact on the BWE of the lower levels.

Displaying descriptive statistics for the two distributions revealed values of the means, maximum and minimum. Table 7.6 shows these descriptive statistics for the normal and Poisson distribution.

Table 7.6: Comparison of descriptive statistics between the normal and Poisson distribution

	Normal distribution			Poisson distribution		
Variable	Mean	Minimum	Maximum	Mean	Minimum	Maximum
BWE distributor	109.70	0.00	1186.90	190.50	0.50	1123.45
BWE wholesaler	16.45	0.02	974.00	31.08	0.15	791.09
BWE retailer	4.93	0.08	460.04	11.31	0.87	103.10

The Normal distribution showed lower means for the BWE retailer, BWE wholesaler and BWE distributor than the Poisson distribution. When it came to maximum values, the Normal distribution had higher values than the Poisson distribution. With minimum values, the Poisson distribution had higher values than the Normal distribution.

These results indicated that the demand distribution had no impact on how the other factors affected the BWE but it only affected the values of the BWE. The Poisson distribution provided lower values of bullwhip than the Normal distribution. Although this dissertation had no interest in the BWE values but rather on how the BWE changes this might not seem important but it was an important observation as it shows the necessity of understanding the demand pattern of an organisation before measuring the BWE.

Similar tests were carried out for the kitchen appliances case study. This case study was modelled first as a normal distribution, then as a lognormal distribution.

7.2.3 Modelling kitchen appliances as a normal distribution

BWE distributor

The significance test results are shown under Table C6.

The p values showed that all the factors in the exception of the demand variance had a significant impact on the BWE distributor.

A main effects plot was again used to test for the difference between means. The main effects plot revealed that the BWE distributor decreased with an increase in distributor inventory adjustment time, wholesaler inventory adjustment time and the retailer inventory adjustment time. The BWE distributor also increased with an increase in the distributor cover time, wholesaler inventory cover time and retailer inventory cover time.

The correlation test shown in Table C7 revealed that the BWE distributor had significant negative correlation with the distributor inventory adjustment time, the wholesaler inventory adjustment time and the retailer inventory adjustment. This meant that the BWE distributor increased as these factors increased. The BWE distributor also had significant positive correlation with the distributor inventory cover time, the wholesaler inventory cover time and the retailer inventory cover time. This meant that the variable increased as these factors increased.

The BWE distribution also had significant positive correlation with the BWE retailer and the BWE retailer. This meant that the BWE distributor also increased as the BWE retailer and the BWE wholesaler increased.

Table C7 also showed that there were no significant positive or negative correlations between the factors under investigation. This meant that there were no interactions between the factors.

BWE wholesaler

Similar significant tests were carried out for the BWE wholesaler. The p values from the Minitab output showed the wholesaler inventory adjustment time, the wholesaler inventory cover time, the retailer inventory adjustment time and the retailer inventory cover time as the only factors that had a significant impact on the BWE wholesaler.

From the main effects plots obtained from Minitab, the patterns for the demand variance, distributor inventory adjustment time and the distributor inventory cover time were almost parallel. This meant that these factors had no impact on the BWE wholesaler. An increase in the wholesaler inventory adjustment time and the retailer inventory adjustment time led to a decrease in the BWE wholesaler. Similarly, increases in the wholesaler inventory cover time and retailer inventory cover time led to an increase in the BWE wholesaler

Table C7 shows that the BWE wholesaler had significant negative correlation with the wholesaler inventory adjustment time and the retailer inventory adjustment time. This meant that the variable decreased as the factors increased. Similarly, the variable had significant positive correlations with the wholesaler inventory cover time and the retailer inventory cover time. This meant that the BWE wholesaler increased as these factors increased.

Similarly, the correlation table showed no significant positive or negative correlations between the factors under investigation. This meant that there were no interactions between the factors under investigation.

BWE retailer

The p values obtained from the Minitab output showed that the retailer inventory adjustment time and the retailer inventory cover time were the only significant factors that had an impact on the BWE retailer.

The main effects plot showed that the BWE retailer decreased with an increase in retailer inventory adjustment time and increased with an increase in retailer inventory cover time. The distributor inventory adjustment time, distributor inventory cover time, wholesaler inventory adjustment time and wholesaler inventory cover time had parallel lines and almost no distinguished patterns. This meant that these factors had no impact on the BWE retailer.

Table C7 showed that the BWE retailer had significant positive and negative correlation with the retailer inventory cover time and the retailer inventory adjustment time respectively. This meant that the factor increased as the retailer inventory cover time increased and the BWE retailer decreased as the retailer inventory adjustment time increased.

The correlation did not show any significant positive or negative correlations between factors. This meant that there were no interactions between the factors under investigation.

7.2.5 Modelling the kitchen appliances as a lognormal distribution

BWE distributor

The p values in Table C8 show that all the factors had a significant impact on the BWE distributor.

The main effects plot for the BWE distributor in Figure C2 revealed that the BWE distributor decreased with an increase in distributor inventory adjustment time, wholesaler inventory adjustment time and the retailer inventory adjustment time. The BWE distributor also increased with an increase in the distributor cover time, wholesaler inventory cover time and retailer inventory cover time.

The correlation output from Minitab is shown in Table C9.The BWE distributor had significant negative correlation with the distributor inventory adjustment time, the wholesaler inventory adjustment time and the retailer inventory adjustment. This meant that the BWE distributor increased as these factors increased. The BWE distributor also had significant positive correlation with the distributor inventory cover time, the wholesaler inventory cover time and the retailer inventory cover time. This meant that the variable increased as these factors increased.

The BWE distribution had significant positive correlation with the BWE retailer and the BWE retailer. This meant that the BWE distributor also increased as the BWE retailer and the BWE wholesaler increased.

From the correlation table, there were no significant positive or negative correlations between the factors under investigation. This meant that there were no interactions between the factors.

BWE wholesaler

The p values obtained from Minitab under Table C10 show the wholesaler inventory adjustment time, the wholesaler inventory cover time, the retailer inventory adjustment time and the retailer inventory cover time as the only factors that had a significant impact on the BWE wholesaler.

From the main effects plots under Figure C2, the patterns for the distributor inventory adjustment time and the distributor inventory cover time are almost parallel. This meant that these factors had no impact on the BWE wholesaler. An increase in the wholesaler inventory adjustment time and the retailer inventory adjustment time led to a decrease in the BWE wholesaler. Similarly, an increased in the wholesaler inventory cover time and the retailer inventory cover time led to an increase in the BWE wholesaler.

Table C9 shows that the BWE wholesaler had significant negative correlation with the wholesaler inventory adjustment time and the retailer inventory adjustment time. This meant that the variable decreased as the factors increased. Similarly, the variable had significant positive correlations with the wholesaler inventory cover time and the retailer inventory cover time. This meant that the BWE wholesaler increased as these factors increased.

From the correlation table, no significant positive or negative correlations were observed. This meant that there were no interactions between the factors under investigation.

BWE retailer

The p values from the Minitab output under Table C11 show that the wholesaler inventory adjustment time, the retailer inventory adjustment time and the retailer inventory cover time were the only significant factors that had an impact on the BWE retailer.

The main effects plot under Figure C2 show that the BWE retailer decreased with an increase in retailer inventory adjustment time and increased with an increase in retailer inventory cover time. The demand variance, distributor inventory adjustment time, distributor inventory cover time and wholesaler inventory cover time had parallel lines and almost no distinguishable patterns. This meant that these factors had no impact on the BWE retailer. The pattern for the wholesaler inventory adjustment time showed an almost parallel line with no distinguishable pattern. From the main effects plot, this meant that the factor had no impact on the BWE retailer although the significant test showed otherwise. This meant that the significance of this factor could have been by chance.

Table C9 shows that the BWE retailer had significant positive and negative correlation with the retailer inventory cover time and the retailer inventory adjustment time respectively. This meant that the factor increased as the retailer inventory cover time increased and the BWE retailer decreased as the retailer inventory adjustment time increased. The BWE retailer showed no significant correlation with the wholesaler inventory adjustment time. This meant that the factor had no impact whatsoever on the BWE retailer as suggested by the significance test.

The correlation table did not show any significant positive or negative correlations between factors. This meant that there were no interactions between the factors under investigation.

7.2.6 Comparison of the normal and lognormal distribution

Using both the normal and lognormal distributions for modelling kitchen appliances demand resulted in the following observations;

- The BWE decreased with an increase in inventory adjustment time at all levels.
- The BWE increased with an increase in inventory cover time at all levels.
- The performance of the uppermost supply chain echelon were impacted by the performance of the lower supply chain levels.
- Factors in the lower echelons of the supply chain may have an impact on the BWE of the upper levels but factors in the upper levels did not have any impact on the BWE of the lower levels.

The Minitab output for the descriptive statistics for the two distributions is shown in Table 7.7. The table reveals that the lognormal distribution had lower values of BWE than the normal distribution. This could mean that the normal distribution does exaggerate BWE values as suggested by Miles (2013).

Table 7.7: Descriptive statistics for the comparison of the normal and the lognormal distributions

	Normal distribution			Lognormal distribution		
Variable	Mean	Minimum	Maximum	Mean	Minimum	Maximum
BWE distributor	15.80	0.10	834.11	11.50	0.08	97.05
BWE wholesaler	4.06	0.08	110.45	6.04	0.09	53.74
BWE retailer	6.26	1.53	25.57	9.53	1.21	25.09

7.2.7 Summary of forward chain results

For the forward chain, the product type and demand distributions had no impact on how the factors under investigation affected the BWE at each echelon of the forward chain. The following findings were true for both product types and the demand distributions:

- The BWE at each echelon increases as the inventory cover time increases.
- The BWE decreases as the inventory adjustment time increases.
- Parameters in the upstream echelons have no impact on the BWE in the lower echelons, but parameters in the downstream echelons do have an impact on the BWE on the upstream echelons.
- The conclusion that the BWE increases as one moves upstream held for all product types and distributions. This meant that the BWE distributor increased with increases in the BWE wholesaler and BWE retailer. Similarly the BWE wholesaler increased when the BWE retailer increased. An inaccurate forecast by the retailer had notable consequences on the BWE of the upstream echelons.

Although the demand distribution had no impact on how the factors under investigation, it did have an impact on the BWE values. The main finding was that the normal distribution had higher values of BWE than the other distributions. This was in agreement with the findings made by Miles (2013).

The closed-loop system

After experimenting with the forward chain with no returns, the reverse chain was introduced with four main scenarios:

1. The BWE in a closed-loop system with returns from the customer for reuse, remanufacturing and cannibalisation without any capacity constraints for both collection and remanufacturing.
2. The BWE in a closed-loop system with returns from the customer and collection capacity constraints but unlimited remanufacturing capacity. In this scenario products were remanufactured as they were collected, according to the PUSH policy described by Van der Laan et al.(1999).
3. Same as scenario 2 but there was no limit to the collection capacity (all products were collected) but the remanufacturing capacity had a limit. In the case where the collected products were more than the remanufacturing capacity, they were carried forward to the next period. Similarly, when the collected products were less than the remanufacturing capacity, no remanufacturing took place in that period until enough products had been collected for remanufacturing.

4. Same as scenario 3 but both the collection and the remanufacturing capacities were limited.

The experimental plans, together with the experimental results of these 4 scenarios are explained in sections 7.3, 7.4, 7.5 and 7.6.

The case studies only performed remanufacturing of products and components and reuse of components and products. It should be noted that both case studies did not perform recycling. This was represented by zeros in the model when the simulations were run. The four scenarios were separated and the models were modified according to each scenario. Again, experiments in these scenarios were based on the forward chains from two case studies. It should also be noted that this dissertation assumed that the company was able to recover all its products from customers. The collection percentage, although it has been a factor of interest in previous research for example that of Das and Dutta (2013), was not a factor of interest in this dissertation. This meant that there was no uncontrollable disposal of products i.e. disposal of products beyond the manufacturer's control.

In the reverse chain, new parameters were introduced based on the return of products by the customer. Some of the parameters did not apply to some scenarios and these were explained as each scenario was simulated. As mentioned before, the reverse chain was based on the forward chains of the two case studies. This meant that in simulating the closed-loop supply chain i.e. the forward chain with the reverse chain incorporated, some variable parameters in the forward chain were fixed to focus only on the reverse chain. Such parameters as the inventory cover time, inventory adjustment time and demand variance had to be fixed at certain levels so that their impact was not considered in the reverse chain. Table 7.8 summarises the fixed and variable parameters in the closed-loop supply chain.

Table 7.8: Parameters in the reverse chain

Parameter	**Value for case A: Electric vehicle batteries**	**Value for case B: Kitchen appliances**
	Fixed parameters	
As usual demand	Poisson(80)	Log Normal (6000,2000)
Components per product	500	15
Production capacity	80 batteries/week	4000 products/week
Delivery time	1 week	1 week
Product production time	1/80 weeks	1/4000 weeks
Component production time	1/(80*500) weeks	1/(4000*15) weeks
Component production capacity	(80*500) components per week	(4000*15) components/week
Inventory cover time at all levels	1.5 weeks	1.5 weeks
Inventory adjustment time at all levels	2 weeks	2 weeks
Inspection time	2 hours	7 minutes
	Variable parameters (under investigation)	
Residence time (weeks)	4,8,16,24	12,36,60,96
Percentage remanufacturable	25, 50,75,100	25,50,75,100
Reprocessing time (hours)	12,15,18,24	0.5,1,1.66,2.17
Collection capacity	65,75, 80 products/week	4000, 6000, 8000 products/week
Remanufacturing capacity	65,75,80 products/ week	4000, 6000, 8000 products/week

The main factors of interest in the reverse chain include:

- The residence time (the time that the customer keeps the product before deciding to return it to the manufacturer).
- The remanufacturing percent (the percentage of collected products that are found to be remanufacturable)
- The reprocessing time (the time it takes to remanufacture a product).
- The collection capacity (the amount of products that the company could collect per unit time based on their resources).
- The remanufacturing capacity (the amount of products that the company could remanufacture per unit time based on their available resources).

Case B not only collected its own sold products but also products from other external sources. The model was modified to account for the external returns. This was done in STELLA by introducing an auxiliary variable named 'external returns' feeding into the available used products. The external returns were defined using equation 7.1. The external returns were assumed to have a similar distribution as the forward chain demand, since they were from various organisations.

$$ER = Log\ Normal(4000{,}2000) \quad (7.2)$$

Where *ER* are the external returns. Introducing the external returns for the kitchen appliances changed the equation for the available used products to equation 7.2.

$$available\ used\ products = DELAY(products\ in\ use, residence\ time) + ER \quad (7.3)$$

Before introducing the reverse chain, parameters in the forward chain were set to fixed values and the simulations were run. All the cover times were set to 1.5 weeks and all the inventory adjustment times were set to 2 weeks. The lognormal demand pattern was selected for the kitchen appliances since it presented lower values of BWE. Similarly the Poisson distribution was selected for electric vehicle batteries. Values of BWE distributor, wholesaler and retailer under these fixed parameters are shown in Table 7.9.

Table 7.9: The BWE for the forward chain with fixed parameters

Demand pattern	Product	BWE distributor	BWE wholesaler	BWE retailer
Lognormal	Kitchen appliances	2.29	1.33	3.07
Poisson	Electric vehicle batteries	36.65	11.43	6.68

7.3 The closed-loop system with no capacity limits

In this scenario, no capacity or remanufacturing limits were introduced and the scenario was similar in its assumptions to those of all the authors on the topic, although in this dissertation it was assumed that the manufacturers collect all of their products. The factors of interest were;

- Remanufacturing percentage
- Residence time
- Reprocessing time

These were only 3 factors with 4 levels. In this case, a full factorial experiment as described by Cimbala (2014) was used. This was because since the number of factors under investigation is small, the number of experiments was also small and there was no need to reduce an already small number. As a result, only 64 simulations were run for each demand pattern. Figure 7.4 shows the experimental plan for this scenario.

7.3.1 Poisson distribution of electric vehicle batteries with no capacity limits

For this scenario, Table 7.10 shows the parameters under investigation and the parameter levels. It should be noted that these parameters were set based on the information provided by the organisation.

Table 7.10: Parameters under investigation for the electric vehicle batteries under a Poisson demand distribution

Parameter	Level 1	Level 2	Level 3	Level 4
Remanufacturing percentage	25	50	75	100
Residence time	4 weeks	8 weeks	16 weeks	24 weeks
Reprocessing time	12 hours	15 hours	18 hours	24 hours

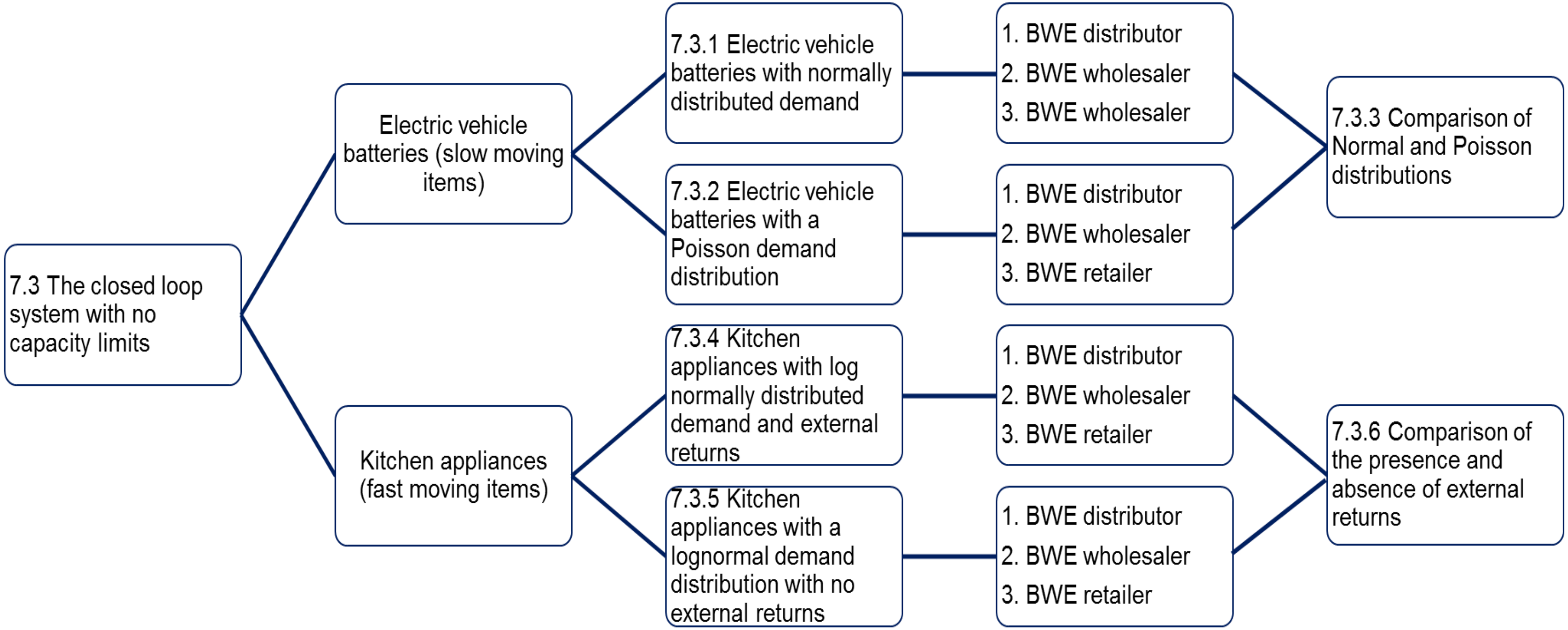


Figure 7.4: Experimental plan for the closed-loop system with no capacity limits

Descriptive statistics

The first stage was to determine how the BWE at all levels changed with the introduction of product returns in the supply chain. This was done by displaying the descriptive statistics from the experiments in Minitab. Figure 7.5 shows a comparison of the descriptive statistics between the forward chain and the reverse chain under this scenario.

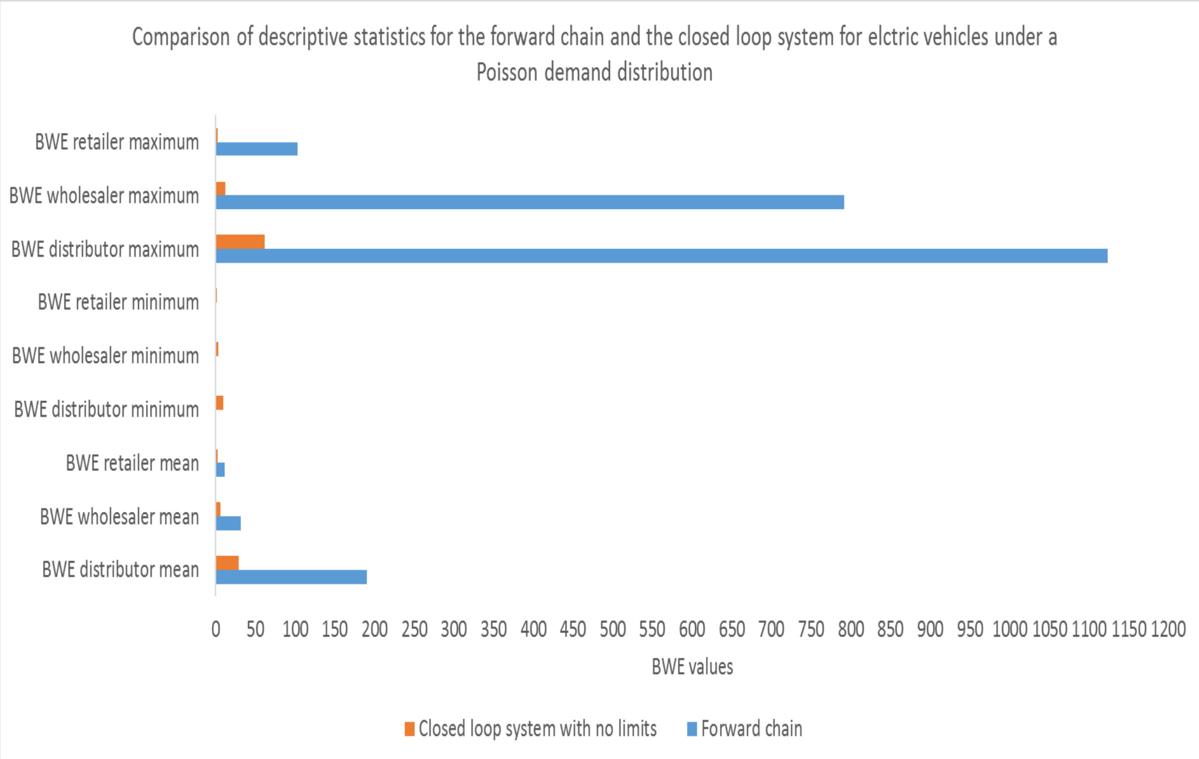


Figure 7.5: Comparison of descriptive statistics between the forward chain and the reverse chain

The mean values for the BWE distributor, wholesaler and retailer decreased with an introduction of product returns into the forward chain at the same level of forward chain parameters. The maximum values of BWE at all echelons of the supply chain also decreased significantly when the reverse chain was introduced.

BWE distributor

The significance test from Minitab in Table 7.11 shows that none of the factors under investigation had any impact on the BWE distributor.

Table 7.11: Significance test for BWE distributor for electric vehicles under Poisson distribution demand and no capacity limits

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	351.54	351.54	117.18	1.72	0.174
Remanufacturing percent	3	307.80	307.80	102.60	1.51	0.223
Reprocess time	3	64.12	64.12	21.37	0.31	0.815
Error	54	3678.75	3678.75	68.12		

Total	63	4402.19			

The main effects of the factors were also investigated using the least squares means table. Table 7.12 shows the least square means for the BWE distributor, BWE wholesaler and the BWE retailer.

Table 7.12: Least squares means table for electric vehicle batteries with a Poisson distribution and no capacity limits

	BWE distributor		**BWE wholesaler**		**BWE retailer**	
Residence time	**Mean**	**SE Mean**	**Mean**	**SE Mean**	**Mean**	**SE Mean**
4	25.688	2.06345	5.266	0.38556	1.729	0.04777
8	26.569	2.06345	5.436	0.38556	1.821	0.04777
16	29.289	2.06345	6.072	0.38556	1.979	0.04777
24	31.643	2.06345	6.525	0.38556	2.081	0.04777
Remanufacturing percent						
25	25.735	2.06345	5.363	0.38556	1.856	0.04777
50	31.753	2.06345	6.460	0.38556	1.952	0.04777
75	28.257	2.06345	5.832	0.38556	1.913	0.04777
100	27.443	2.06345	5.644	0.38556	1.890	0.04777
Reprocessing time						
0.300	27.572	2.06345	5.685	0.38556	1.889	0.04777
0.375	28.284	2.06345	5.761	0.38556	1.884	0.04777
0.450	29.933	2.06345	6.097	0.38556	1.915	0.04777
0.600	27.400	2.06345	5.756	0.38556	1.922	0.04777

The BWE distributor increased with an increase in residence time. Delaying the return of products by increasing residence time made the model behave like the original forward chain without any returns.

Table 7.12 indicates that the BWE distributor increased with an increase in the time that the customer kept the product before returning it. The reprocessing time did not seem to have an impact on the BWE distributor. This is because it is very small compared with the residence time, based on the data provided by the organisation. The BWE distributor increased with an increase in remanufacturing percentage from 25 percent to 50 percent but it showed a decreasing trend with an increase in remanufacturing percent as more products continued to be remanufactured.

Table 7.13 is the correlation output from Minitab.

The BWE distributor had a significant positive correlation with the residence time which meant that it increased as the residence time increased. The BWE distributor also had significant positive correlation with the BWE retailer and the BWE wholesaler. This meant that as these two levels' BWE increased, the BWE distributor increased. In this case, the conclusion that the BWE increased as one goes upstream held.

Table 7.13: Correlation output for electric vehicles under Poisson demand and no capacity limits

	Residence time	Remanufacturing percent	Reprocessing time	BWE distributor	BWE wholesaler
Remanufacturing percent	-0.019 ***0.879***				
Reprocess time	0.000 ***1.000***	-0.002 ***0.986***			
BWE distributor	0.282 ***0.024***	0.003 ***0.979***	-0.007 ***0.958***		
BWE wholesaler	0.321 ***0.010***	-0.003 ***0.980***	0.022 ***0.861***	0.992 ***0.000***	
BWE retailer	0.601 ***0.000***	0.011 ***0.928***	0.063 ***0.618***	0.799 ***0.000***	0.855 ***0.000***
Cell contents: correlation ***p-values***					

BWE wholesaler

Similar to the BWE distributor, the significance test output shown in Table 7.14 showed that none of the factors under investigation was significant as far as the BWE wholesaler was concerned.

Table 7.14: Significance test for the BWE wholesaler for electric vehicle batteries under a Poisson demand distribution with no capacity limits

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	16.221	13.323	4.441	1.88	0.145
Remanufacturing percent	4	14.312	13.415	3.354	1.42	0.241
Reprocess time	3	0.736	0.736	0.245	0.10	0.958
Error	53	125.423	125.423	2.366		
Total	63	156.692				

Table 7.12 shows that the BWE wholesaler increased with an increase in residence time. The table did not show distinct patterns for the reprocess time and the remanufacturing percentage.

From Table 7.13, it can be seen that the BWE wholesaler had significant positive correlation with the residence time. This meant that it increased with an increase in residence time. The correlation test also showed no interaction between factors.

BWE retailer

The test for significance is shown in Table 7.15. This test shows that the residence time was the only significant factor where the BWE retailer was concerned.

Table 7.15: Significance test for the BWE retailer for electric vehicle batteries under a Poisson demand distribution with no capacity limits

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	1.19410	1.08837	0.36279	9.94	0.000
Remanufacturing percent	4	0.11905	0.11600	0.02900	0.79	0.534
Reprocess time	3	0.01406	0.01406	0.00469	0.13	0.943
Error	53	1.93367	1.93367	0.03648		
Total	63	3.26088				

Table 7.12 shows that the BWE retailer increased with an increase in residence time. The same output showed no distinct patterns for the reprocessing time and the remanufacturing percentage.

From Table 7.13, the BWE retailer had significant positive correlation with the residence time. This meant that it increased with an increase in residence time.

Because the results showed the other factors as being insignificant, one couldn't help but wonder if the demand distribution did have an impact on how the other factors had an impact on the BWE. For this reason, the same scenario for electric vehicles was run with the demand distribution modelled as a normal distribution.

7.3.2 Normal distribution of electric vehicle batteries with no capacity limits

The demand pattern was changed to a normal distribution to see if the demand distribution had any impact at all on how the factors affected the BWE in the forward chain.

BWE distributor

The significance output for the BWE distributor under Table C12 shows that none of the factors were significant as far as the BWE distributor was concerned.

Table C13 shows the difference between means. The table shows that the BWE distributor increased with an increase in the residence time. The same table showed no distinctive pattern for the reprocessing time and the remanufacturing percentage. This was similar to the case when the demand distribution for electric vehicle batteries was modelled as a Poisson distribution. This meant that the demand distribution had no impact on how the factors affected the BWE distributor for electric vehicle batteries.

The correlation test is also shown under Table C14. This test shows that the BWE distributor only had significant positive correlation with the BWE wholesaler and the BWE retailer. This meant that the BWE increased as one moved upstream.

Table C14 also shows no significant positive or negative correlations between the factors under investigation which meant that there were no interactions between factors.

BWE wholesaler

The significance test for the BWE wholesaler is shown under Table C15.The table shows that the residence time as the only significant factor where the BWE wholesaler was concerned. This was similar to the Poisson demand output. In this case again, the demand distribution had no impact on how the factors affected the BWE wholesaler.

Table C13 shows that the BWE wholesaler increased with an increase in residence time. The same table also showed no distinctive pattern for the remanufacturing percentage and the reprocessing time.

From the correlation test under Table C14, the BWE wholesaler had significant positive correlation with the residence time. This meant that the BWE wholesaler increased as the residence time increased.

BWE retailer

Table C16 shows the output of the significance test from Minitab. The table shows that the residence time was the only significant factor as far as the BWE retailer was concerned.

Form the Table C13, the BWE retailer showed a distinctive pattern with the residence time. The BWE retailer increased with an increase in residence time but it showed no distinctive pattern with the remanufacturing percentage and the reprocessing time.

The correlation test under Table C14 shows that the BWE retailer only had significant positive correlation with the residence time. This meant that the BWE retailer increased as the residence time increased.

7.3.3 Comparison of results for the Poisson distribution and the normal distribution for electric vehicles with no capacity limits

The two demand distributions displayed the same results. Because of this, there is significant evidence at the 95% level of confidence that only the residence time had an impact on the BWE for electric vehicle batteries. The results also showed that the demand distribution pattern had no impact on how the factors had an impact on the BWE in the closed-loop system with no capacity limits.

However, the normal distribution showed higher values of BWE at all levels as shown by the least squares means tables. This again confirmed the findings of Miles (2013) that the normal distribution exaggerates BWE values.

7.3.4 Kitchen appliances with a lognormal distribution demand pattern, no capacity limits and external returns

Table 7.16 shows the parameters under investigation and their levels. The parameter ranges for residence time and reprocessing times were based on the information provided by the company.

Table 7.16: Factor levels for Kitchen appliances with no capacity limits

Parameter	Level 1	Level 2	Level 3	Level 4
Remanufacturing percentage	25	50	75	100
Residence time	12 weeks	36 weeks	60 weeks	96 weeks
Reprocessing time	30minutes	60 minutes	100minutes	130 minutes

Descriptive statistics

Figure 7.6 shows a comparison of the descriptive statistics between the forward chain and the reverse chain as obtained from Minitab after introducing the closed-loop system.

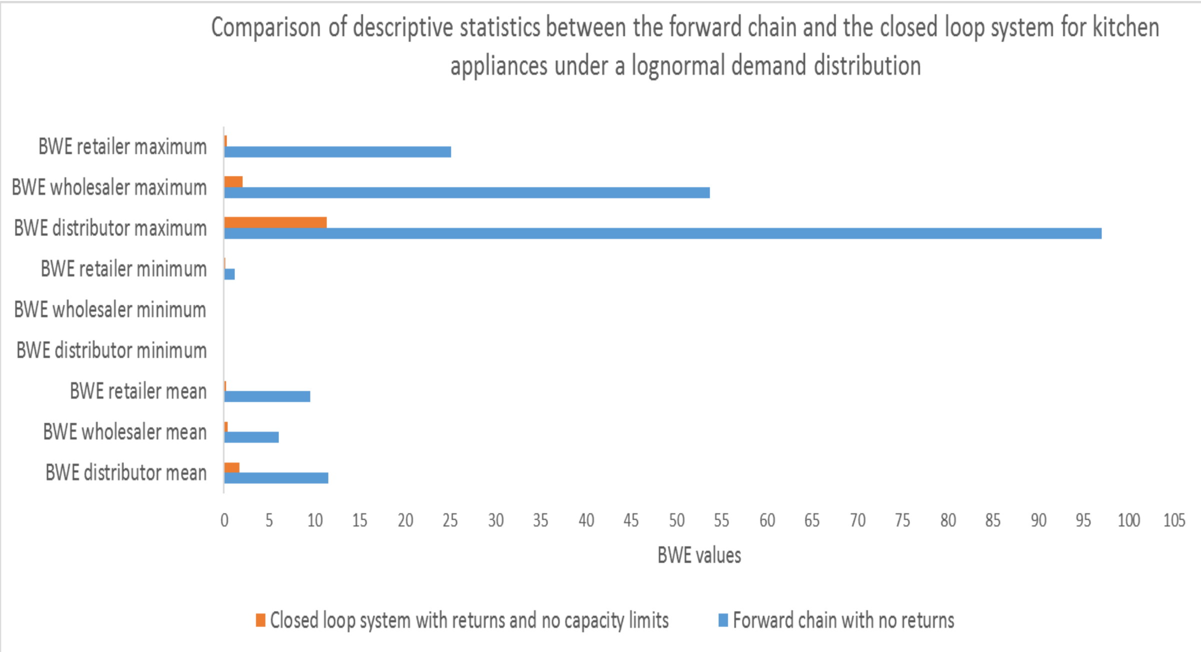


Figure 7.6: Comparison of descriptive statistics between the forward chain and the closed-loop system for kitchen appliances under a lognormal demand distribution

The means, minimum and maximum values of BWE at all levels decreased significantly. At some point the levels were damped (i.e. BWE less than 1). This agreed with the conclusions that introducing product returns decreases the BWE in a supply chain.

BWE distributor

The test for significance under Table C17 had p-values that showed that none of the factors under investigation had any impact on the BWE distributor.

The least squares means table, Table C18, shows that although the means of the BWE distributor did change and were not equal, there was no distinct pattern demonstrated by the three factors under investigation. They had mixed patterns which was unclear how they impacted the BWE distributor.

Table C19 shows the correlation output. From the correlation table, although the BWE distributor had negative correlation with the factors under investigation, it was insignificant with p-values greater than 0.05. There was no significant positive or negative correlation between the factors. This meant that there were no interactions present.

BWE wholesaler

For the BWE wholesaler, the significance test under Table C20 also shows that none of the factors under investigation had any impact on the BWE wholesaler.

From Table C18, there was no distinct pattern as to how the factors also affected the BWE wholesaler although the means were really different.

The BWE similarly had no significant correlation with any of the factors under investigation so it was unclear how the factors impacted the BWE wholesaler. The BWE wholesaler, however, had significant positive correlation with the BWE distributor and the BWE retailer.

BWE retailer

The BWE retailer produced similar results to the BWE wholesaler and the BWE distributor in all tests.

Because of these outcomes, it became necessary to investigate if the presence of external returns had an impact on how the factors affected the BWE in the supply chain. This was because the external returns were always present all the time and were not regulated by company factors. For this reason, simulations were run for the kitchen appliances without the external returns.

7.3.5 Kitchen appliances with a lognormal distribution demand pattern, no capacity limits and no external returns

1. **Descriptive statistics**

Figure 7.7 displays a comparison of the descriptive statistics for the kitchen appliances. The descriptive statistics in the Figure were for the forward chain with no returns, the closed-loop system with external returns and the closed-loop system without external returns.

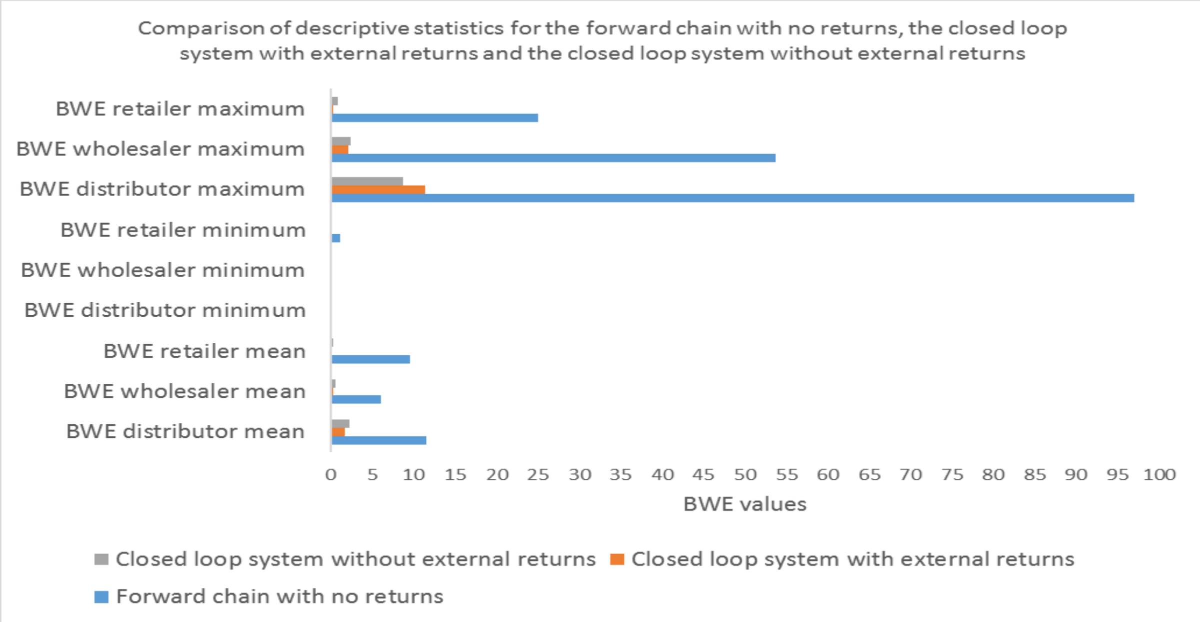


Figure 7.7: Comparison of descriptive statistics for the forward chain with no returns, the closed-loop system with external returns and the closed-loop system without external returns

The means for the BWE distributor, wholesaler and retailer were higher in the absence of external returns, although they were lower than the BWE of the original supply chain without any product returns. This was similar for the maximum and the minimum values of the BWE.

BWE distributor

The test for significance of factors under Table C21 shows that the residence time and the remanufacturing percentage were the only significant factors as far as the BWE distributor was concerned. This was a different outcome from the same model with external returns. This meant that external returns do have an impact on how the factors impacted the BWE distributor.

Table C22 shows the least squares means table for this scenario as obtained from Minitab. The table clearly shows the means of the BWE distributor decreasing as the residence time decreased. The means for the BWE distributor increased when the remanufacturing percentage was increased to 50% but the decreased as the remanufacturing percentage was increased.

The least squares means table shows no distinctive patterns for the reprocessing time. Although the means for the reprocessing time were not equal, it was unclear how it impacted the BWE distributor. This was because the time taken to remanufacture the products was too small compared to the residence time and its impact was overshadowed by the residence time.

The result for the correlation, Table C23 revealed that the BWE distributor had significant positive correlation with the residence time. This meant that the BWE distributor increased as the residence time increased. The BWE distributor also had significant negative correlation with the remanufacturing percent. This meant that the BWE distributor decreased as the remanufacturing percentage increased. There was a significant positive correlation between the BWE distributor, BWE wholesaler and BWE retailer. This meant that the conclusion that the BWE increased as one goes upstream still held in this situation. From the correlation outcome, there were no significant positive or negative correlations between the factors under investigation. This meant that there were no interactions between the factors under investigation.

BWE wholesaler

The BWE wholesaler displayed similar results to the tests as the BWE distributor. This meant that the presence of external returns did have an impact on how the factors affected the BWE wholesaler as well. The BWE wholesaler increased with an increase in residence time and decreased with and decreased with an increase in remanufacturing percent. There was no significant pattern for the reprocessing time as shown in Table C22.

BWE retailer

The BWE retailer also demonstrated similar patterns to the BWE wholesaler and the BWE distributor. It was only impacted by the residence time and the remanufacturing percentage. The BWE retailer increased with an increase in residence time and decreased with an increase in remanufacturing percentage.

7.3.6 Comparison of results for kitchen appliances with and without external returns

The results for the kitchen appliances can be summarised using the following points:

- The results showed that, for kitchen appliances, the introduction of product returns reduced the BWE at all levels of the supply chain.
- The presence of external returns produced lower values of BWE at all levels than without external returns.
- The presence of external returns also had an impact on how the factors affected the BWE since these were not regulated by the company and were returned at any time by the external parties.
- The residence time and the remanufacturing percentage were the only significant factors as far as the BWE at all levels was concerned. The BWE increased as the residence time increased. For the remanufacturing percentage, the BWE increased when the percentage was increased from 25 percent to 50 percent, then it started decreasing as the remanufacturing percentage increased.

7.4 The closed-loop system with collection capacity limits only

After investigating the closed-loop supply chain with no capacity limits, collection capacity limits were introduced to the system. Collection capacity limits controlled how much the company was able to collect, given that it was able to get all its used products from customers. Similar to the other scenarios, the experimental plan for this scenario is shown in Figure 7.8.

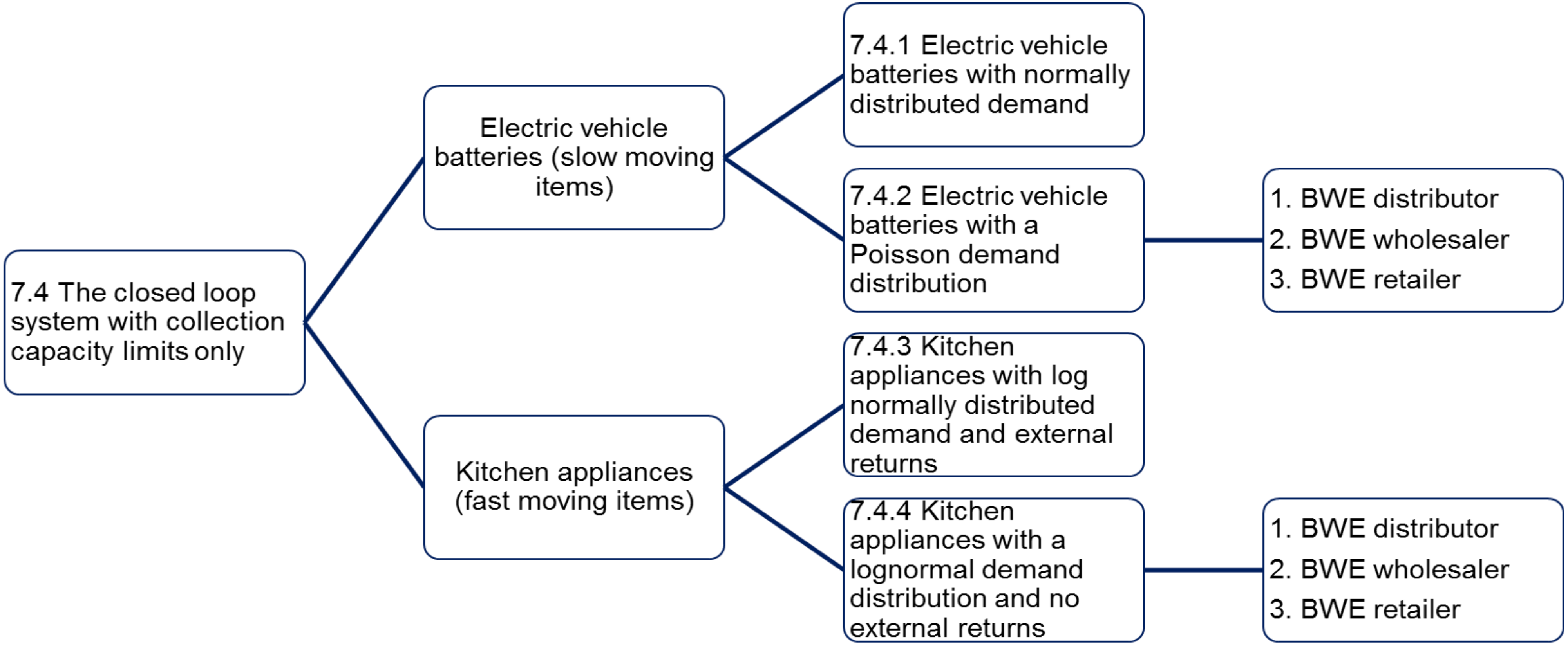


Figure 7.8: Experiment plan for the closed-loop system with collection capacity limits

7.4.1 Poisson distribution for electric vehicle batteries with collection capacity limits only

The rest of the parameters were kept at the same levels. A fourth parameter was introduced, the collection capacity was introduced in this scenario and it had 3 levels as shown in Table 7.17.

Table 7.17: Factor levels for electric vehicle batteries with collection capacity limits

Parameter	Level 1	Level 2	Level 3	Level 4
Remanufacturing percentage	25	50	75	100
Residence time	4 weeks	8 weeks	16 weeks	24 weeks
Reprocessing time	12 hours	15 hours	18 hours	24 hours
Collection capacity	65	75	80	-

Descriptive statistics

After introducing the collection capacity limits, it was necessary to compare the descriptive statistics with those of both the forward chain and the closed-loop system without any capacity limits. Figure shows this comparison.

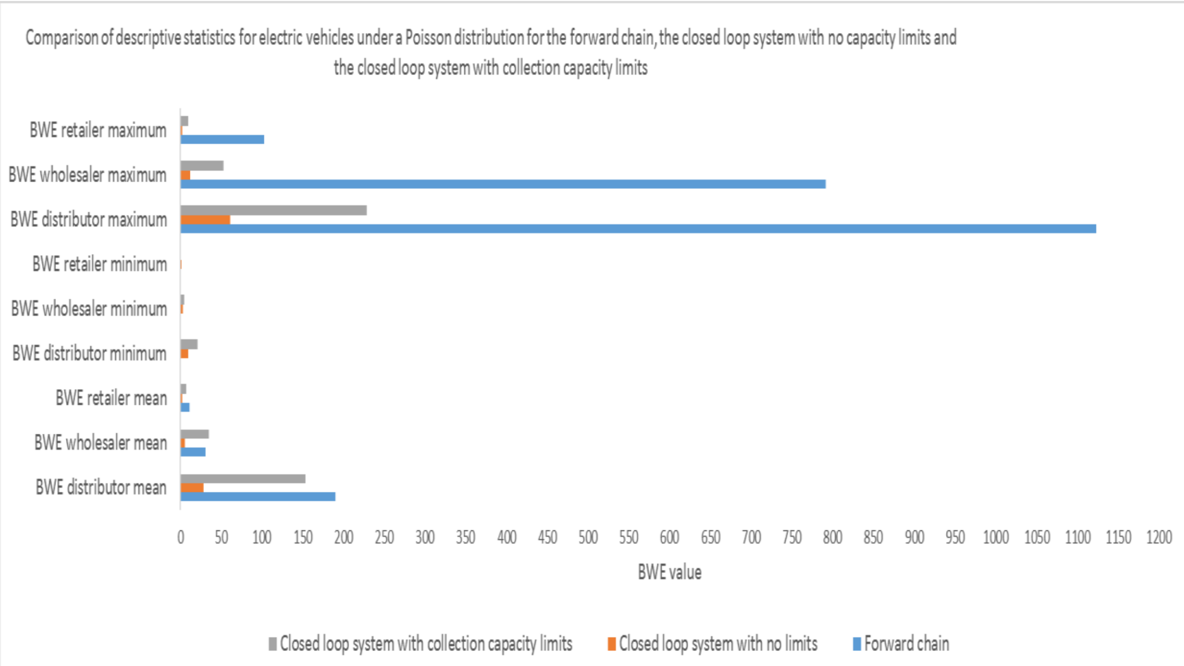


Figure 7.9: Comparison of descriptive statistics for electric vehicles under a Poisson distribution for the forward chain, the closed-loop system with no capacity limits and the closed-loop system with collection capacity limits

The Figure shows that the BWE at all levels increased with the introduction of collection capacity limits but it was still lower than the BWE in the forward chain with no product returns.

BWE distributor

The significance test for the BWE distributor under Table C24 shows that the residence time, the remanufacturing percentage and the collection capacity were significant as far as the BWE distributor was concerned.

The difference between means shown in Table C25, explains how the introduction of collection capacity limits impacted The BWE distributor. The table shows that the BWE distributor increased with an increase in residence time, remanufacturing percentage and collection capacity limits. This meant that as collection capacity limits were introduced to the system, The BWE distributor increased and the value increased as the capacity limits increased. In this case the results showed that the more products collected and remanufactured, the greater the BWE distributor. The BWE distributor increased with the introduction of collection capacity limits, but as the limits were increased, the variable also increased.

Table C26 shows the correlation output from Minitab for electric vehicles with collection capacity limits. The BWE distributor had significant positive correlation with the residence time, the remanufacturing percentage and the collection capacity. This meant that the BWE distributor increased as these factors increased. The BWE distributor also had significant positive correlation with the BWE wholesaler and the BWE retailer. This meant that the conclusion that the BWE increased as one moved upstream still held in this case.

There were no significant positive or negative correlations between the factors. This meant that there were no interactions between factors.

BWE wholesaler

As in the previous scenarios, the BWE wholesaler showed a similar pattern to the BWE distributor. The only difference in this case was that the BWE wholesaler was lower than the BWE distributor as an echelon closer to the demand. The BWE wholesaler increased with an increase in residence time, remanufacturing percentage and collection capacity.

BWE retailer

Again, the BWE retailer behaved in a similar way to the BWE distributor and the BWE wholesaler. The BWE retailer increased with an increase in the residence time, the remanufacturing capacity and the collection capacity.

7.4.2 Normal distribution for electric vehicle batteries with collection capacity limits

Because modelling the electric vehicle batteries as a normal distribution produced similar results, it was not necessary to repeat the same experiments. Again, the demand distribution had no impact on how the factors affected the BWE in the closed-loop system.

7.4.3 Lognormal distribution of kitchen appliances with collection capacity limits and external returns

Again the other parameters were kept constant in this case and collection capacity limits were introduced. Table 7.18 shows the parameters in this case and their levels.

Table 7.18: Factors for kitchen appliances with collection capacity limits

Parameter	Level 1	Level 2	Level 3	Level 4
Remanufacturing percentage	25	50	75	100
Residence time	12 weeks	36 weeks	60 weeks	96 weeks
Reprocessing time	30minutes	60 minutes	100minutes	130 minutes
Collection capacity	4000 products/week	6000 products/week	8000 products/week	-

The outcomes of the experiments for the kitchen appliances with the collection capacity limits and external returns were similar to the same products with no collection capacity limits and external returns. Although the descriptive statistics for the kitchen appliances with collection capacity limits showed higher bullwhip values, the other tests showed that in the presence of external returns, the impact of the factors under investigation was insignificant. For this reason again, it was necessary to ignore the external returns and find out if the impact of the factors changed.

7.4.4 Lognormal distribution of kitchen appliances with collection capacity limits and no external returns

Descriptive statistics

A comparison of descriptive statics for when the collection capacity limits were introduced to the kitchen appliances is shown in Figure 7.10.

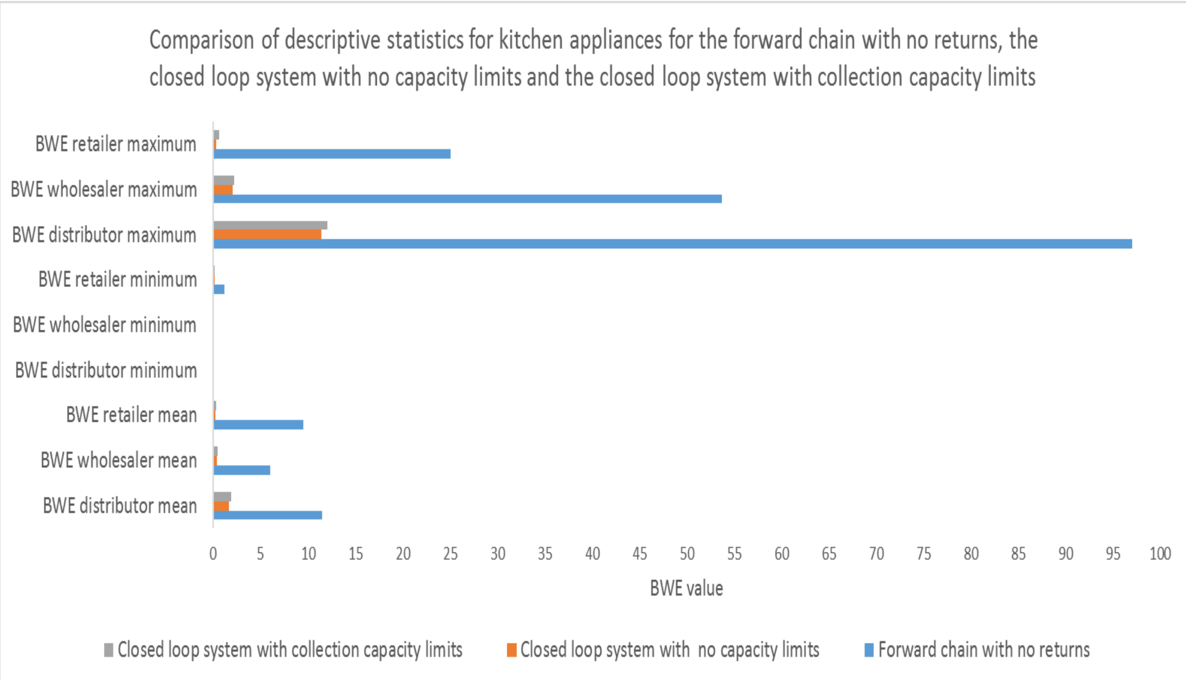


Figure 7.10: Comparison of descriptive statistics for kitchen appliances for the forward chain with no returns, the closed-loop system with no capacity limits and the closed-loop system with collection capacity limits

The introduction of collection capacity limits to the kitchen appliances without external returns, showed higher mean values of BWE distributor, wholesaler and retailer compared to those with no capacity limits.

BWE distributor

Table C27 shows the test for significance for the BWE distributor. With the removal of external returns, the BWE distributor was significantly affected by the residence time and the collection capacity limits as indicated by the p-values.

The least squares means shown in Table C28 indicate that the BWE distributor increased with an increase in residence time, but it decreased with an increase in collection capacity limits. This was a different result with that of the electric vehicle batteries. This could mean that the size and speed of the demand might have an impact on how the factors impact the BWE.

The correlation output is also shown in Table C29. From Table C29, the BWE distributor had significant positive correlation with the residence time. This meant that as the residence time increased, the BWE distributor increased. The same variable had a significant negative correlation with the collection capacity. This meant that as the collection capacity increased, the BWE distributor decreased. The more products that were collected, the lower the BWE distributor.

From the correlation table, there were no significant positive or negative correlations between the factors under investigation. This meant that there was no interaction between the factors. The significant positive correlations between the BWE distributor, BWE wholesaler and BWE retailer also showed that the conclusion that BWE increases as one moves upstream held.

BWE wholesaler

The BWE wholesaler behaved in a similar way to the BWE distributor. The BWE wholesaler increased with an increase in residence time. The same variable decreased with an increase in collection capacity.

BWE retailer

The BWE retailer also behaved in a similar way to the BWE distributor and the BWE wholesaler. It increased with an increase in residence time and decreased with an increase in collection capacity.

7.4.5 Comparison of results for the electric vehicle batteries and the kitchen appliances after the introduction of collection capacity limits

The results of this scenario are best summarised by the following points:

- After the introduction of collection capacity limits, both products experienced increases in BWE values compared to the scenario with no capacity limits.
- The products differed in how they responded to the increment of the collection capacity limits. The electric vehicle batteries (slow moving and low demand items) experienced increases in BWE values at all levels as the collection capacity limits were increased. The kitchen appliances (fast moving, high demand items) experienced decreases in BWE values as the capacity limits were increased.

The general outcome is that, the introduction of collection capacity limits to a closed-loop system led to an increase in the BWE.

7.5 The closed-loop system with remanufacturing capacity limits only

In this scenario, the closed-loop system was modelled with remanufacturing limits only, without any collection limits. In this scenario, it was assumed that the organisation only remanufactured products when it had collected enough for remanufacture. In this case, the remanufacturing capacity limits represent the both the minimum amount of products that have to be collected for remanufacturing and the maximum amount of products that can be remanufactured per week. This meant that when the products were less than the remanufacturing capacity, there was no remanufacturing in that period and products were carried over to the next period. Similarly, when the collected products were more than the remanufacturing capacity, the extra products were carried over to the next period as backlogs. Similar to the previous sections, the experiment plan for this scenario is shown in Figure 7.11.

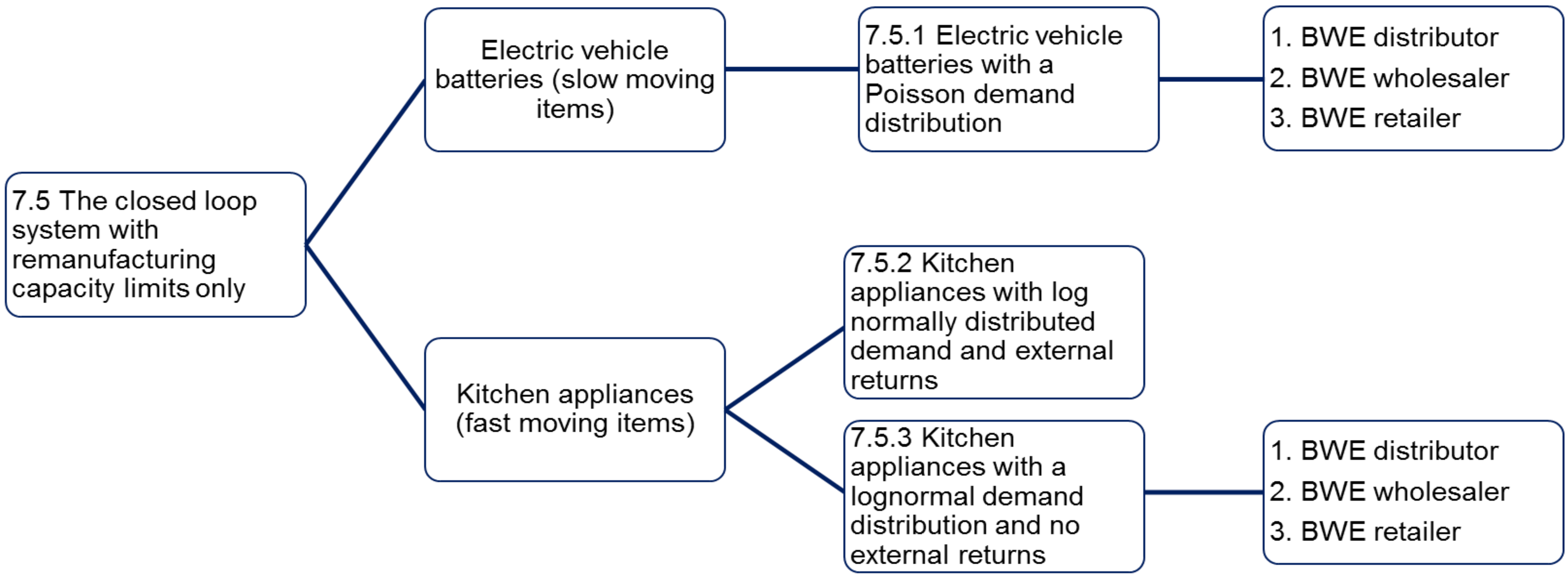


Figure 7.11: Experimental plan for the closed-loop system with remanufacturing capacity limits only

The experimental plan for this scenario no longer shows a comparison of demand distributions for electric vehicles because the normal distribution has proven to behave in a similar way to the Poisson distribution. It was not necessary to keep repeating experiments with similar results.

7.5.1 Poisson distribution for electric vehicle batteries with remanufacturing capacity limits only

The rest of the parameters were kept at the same levels. A fourth parameter was introduced, the remanufacturing capacity was introduced in this scenario and it had three levels as shown in Table 7.19. The remanufacturing capacities were given similar factor levels to the collection capacity limits.

Table 7.19: Factor levels for electric vehicle batteries with remanufacturing capacity limits

Parameter	Level 1	Level 2	Level 3	Level 4
Remanufacturing percentage	25	50	75	100
Residence time	4 weeks	8 weeks	16 weeks	24 weeks
Reprocessing time	12 hours	15 hours	18 hours	24 hours
Remanufacturing capacity	65	75	80	-

Descriptive Statistics

For the electric vehicle batteries, descriptive statistics were compared for the forward chain, the closed-loop system with no capacity limits, the closed-loop system with collection capacity limits only and the closed-loop system with remanufacturing capacity limits only. Figure 7.12 shows a comparison of these descriptive statistics.

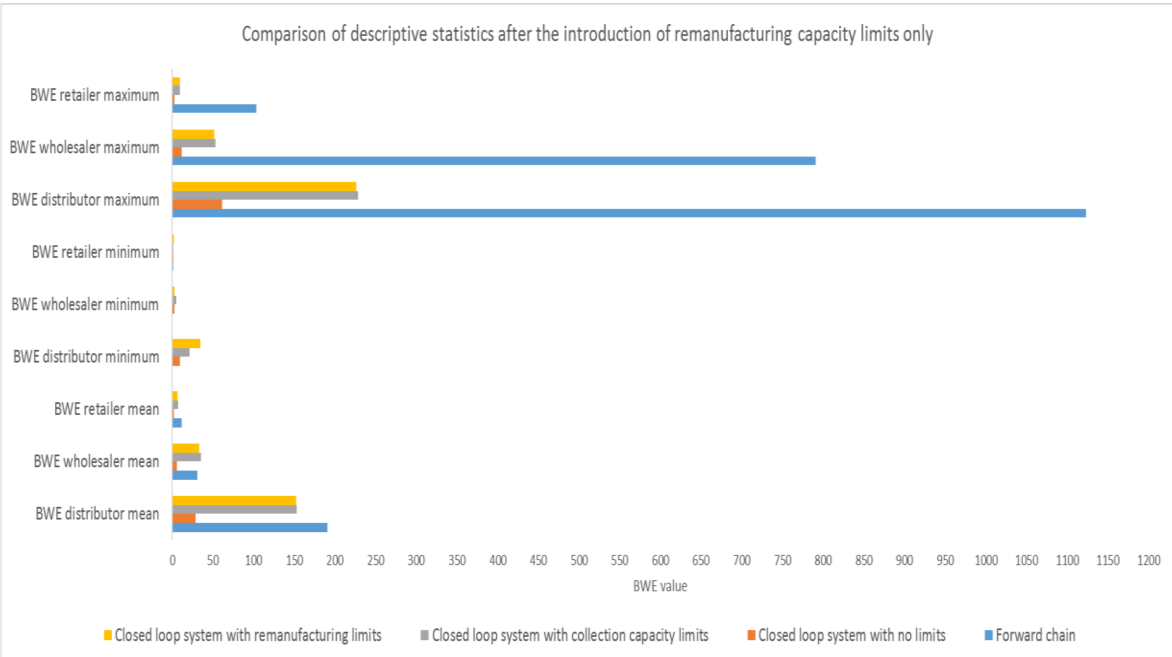


Figure 7.12: Comparison of descriptive statistics after the introduction of remanufacturing capacity limits only

The descriptive statistics in Figure 6.39 show that the means for the BWE distributor, BWE wholesaler and BWE retailer were almost similar to those for the same products with collection capacity limits only. The BWE values at all levels increased when remanufacturing capacity limits were introduced to the closed-loop system without capacity limits. The values however were still less than the forward chain with no returns.

BWE distributor

The significance tests under Table C30 indicate through the p-values that the residence time was the only significant factor as far as the BWE distributor was concerned.

The main effects plot for the BWE distributor shown in Figure 7.13, showed different results from the significance test.

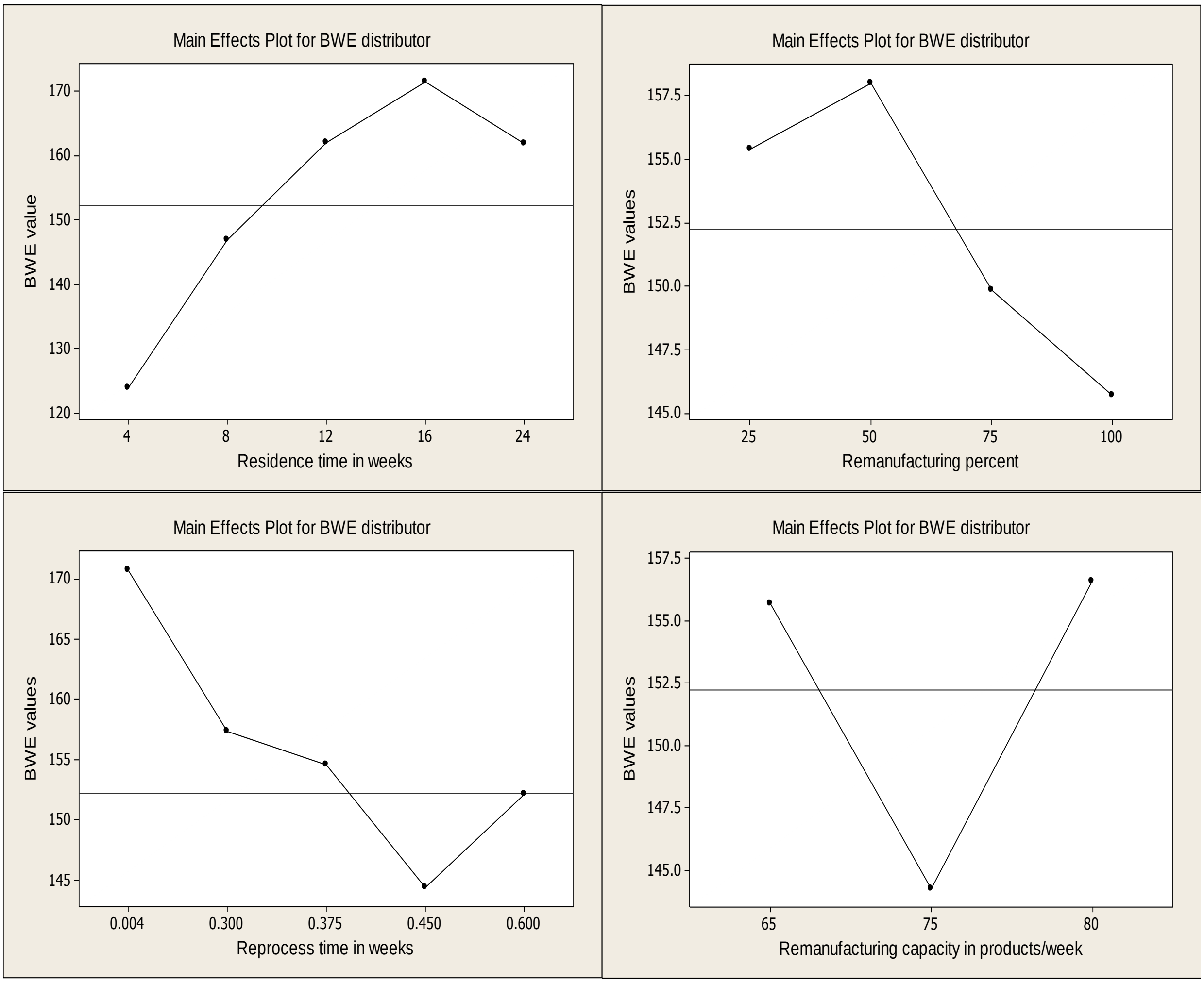


Figure 7.13: Main effects plots for BWE distributor for electric vehicles under a Poisson demand distribution with remanufacturing capacity limits only

From the plot, the BWE distributor increased with an increase with residence time up to some point, Similar to the previous scenario, the BWE distributor increased when the remanufacturing percentage was increased to 50 percent but decreased as the remanufacturing percentage continued increasing. Although the line for the remanufacturing capacity was not horizontal, there was no distinguished pattern on how the remanufacturing capacity affected the BWE distributor. The BWE distributor also decreased with an increase in the reprocess time up to some point as indicated in the main effects plot. This was different from the previous scenario where the reprocessing time had no impact at all.

The correlation output under Table C31 shows that the BWE distributor only had a significant positive correlation with the residence time. This meant that the BWE distributor increased as the residence time increased.

Again, the correlation table showed no significant positive or negative correlations between the factors. This meant that there were no interactions between the factors under investigation.

BWE wholesaler

The BWE wholesaler behaved in the same way as the BWE distributor. It produced similar significance test results. From the significance test, the residence time was the only significant factor as far as the BWE wholesaler was concerned. The main effects plot also was similar to the BWE distributor. The BWE wholesaler increased with an increase in residence time up to 16 weeks and started to decrease. The BWE decreased with an increase in remanufacturing percent. Similarly, the BWE decreased with an increase in reprocessing time up to a point and started increasing. The remanufacturing capacity showed no distinct pattern although the line was not parallel. The main effect plot for the BWE wholesaler is shown under Figure C3.

The correlation test in Table C31 shows that the BWE wholesaler only had significant positive correlation with the residence time. This meant that the BWE wholesaler increased as the residence time increased.

BWE retailer

The test for significance of factors under Table C32 shows that the residence time and the remanufacturing percentage were the only significant factor as far as the BWE retailer was concerned.

The main effects plot for the BWE retailer shown in Figure C4 was similar to that of the BWE distributor. The BWE retailer increased with increasing residence time, decreased with increasing remanufacturing percentage. The same variable produced no distinct patterns for the reprocessing time and the remanufacturing capacity.

Table C31 shows that the BWE retailer had significant positive correlation with the residence time. This meant that the BWE wholesaler increased as the residence time increased. The BWE retailer also had significant negative correlation with the remanufacturing percentage. This meant that the BWE retailer decreased with an increase in remanufacturing percentage.

In this case the remanufacturing capacity limits had no distinguished impact on the BWE effect in the closed-loop system and their impact was deemed to be insignificant.

7.5.2 Lognormal distribution for kitchen appliances with remanufacturing capacity limits and external returns

Table 7.20 shows the factors that were under investigation in this scenario.

Table 7.20: Parameters for the kitchen appliances with remanufacturing limits only

Parameter	Level 1	Level 2	Level 3	Level 4
Remanufacturing percentage	25	50	75	100
Residence time	12 weeks	36 weeks	60 weeks	96 weeks
Reprocessing time	30minutes	60 minutes	100minutes	130 minutes
Remanufacturing capacity	4000 products/week	6000 products/week	8000 products/week	-

Similar to the previous simulations, in the presence of external returns, all the factors under investigation had no significant impact on the BWE in the supply chain. This meant that the presence of external returns does have an impact on how factors affected the BWE at all levels in the supply chain.

For this reason, the same scenario was ran again without external returns.

7.5.3 Lognormal distribution for kitchen appliances with remanufacturing capacity limits and no external returns

Descriptive statistics

Figure 7.14 shows a comparison of descriptive statistics for kitchen appliances after the introduction of remanufacturing capacity limits to the closed-loop system. This scenario was compared to the forward chain with no returns, the closed-loop system with no capacity limits and the closed-loop system with collection capacity limits only.

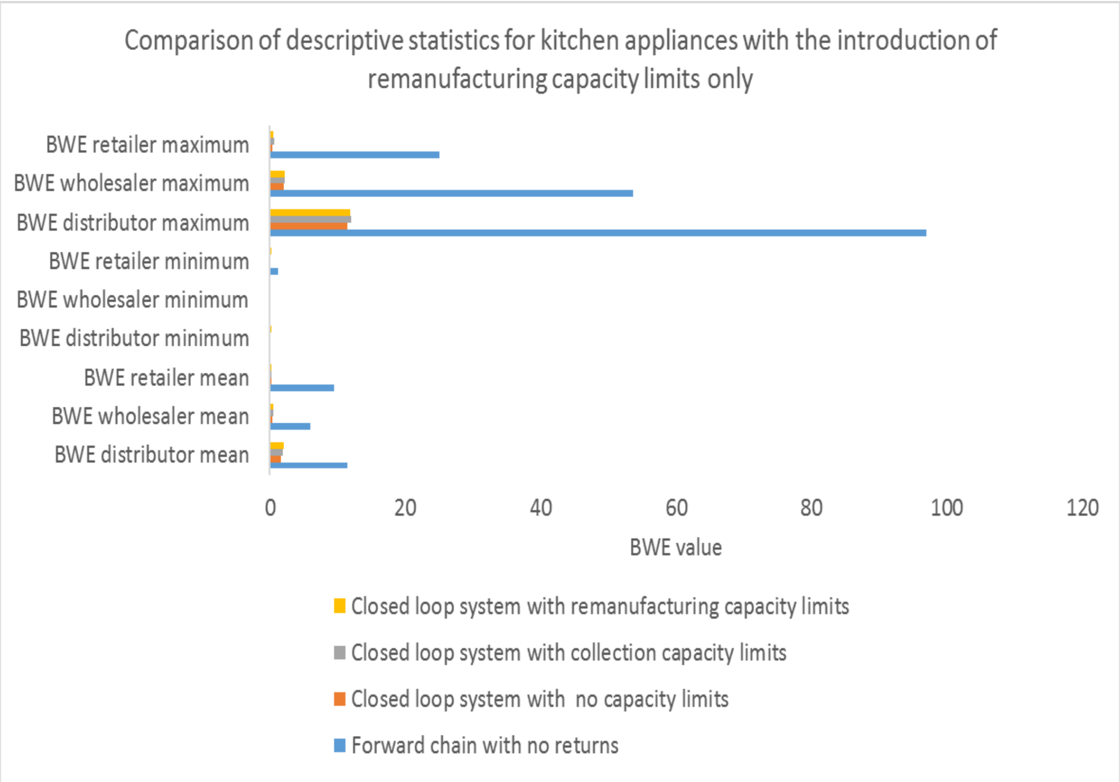


Figure 7.14: Comparison of descriptive statistics for kitchen appliances with the introduction of remanufacturing capacity limits only

Similar to the electric vehicle batteries, the closed-loop system with remanufacturing capacity limits only had similar values to the closed-loop system with collection capacity limits only. The two had values of BWE lower than the forward chain with no product returns but higher than the closed-loop system with no capacity limits. This means that the introduction of capacity limits does increase BWE values.

BWE distributor

The presence of the remanufacturing limits affected how the other factors impacted the BWE distributor. As shown in the main effects plot in Figure 7.15, the BWE distributor increased with remanufacturing limits. This could have been because of the introduction of remanufacturing backlogs whenever collected products were less than the remanufacturing capacity. However, this effect led to factors such as remanufacturing percentage, residence time and reprocessing time having no distinguished impact on the variable.

In the case of remanufacturing limits, the BWE distributor increased with an increase in the remanufacturing capacity. This was different for the collection capacity limits, the BWE distributor decreased with an increase in collection capacity for the kitchen appliances.

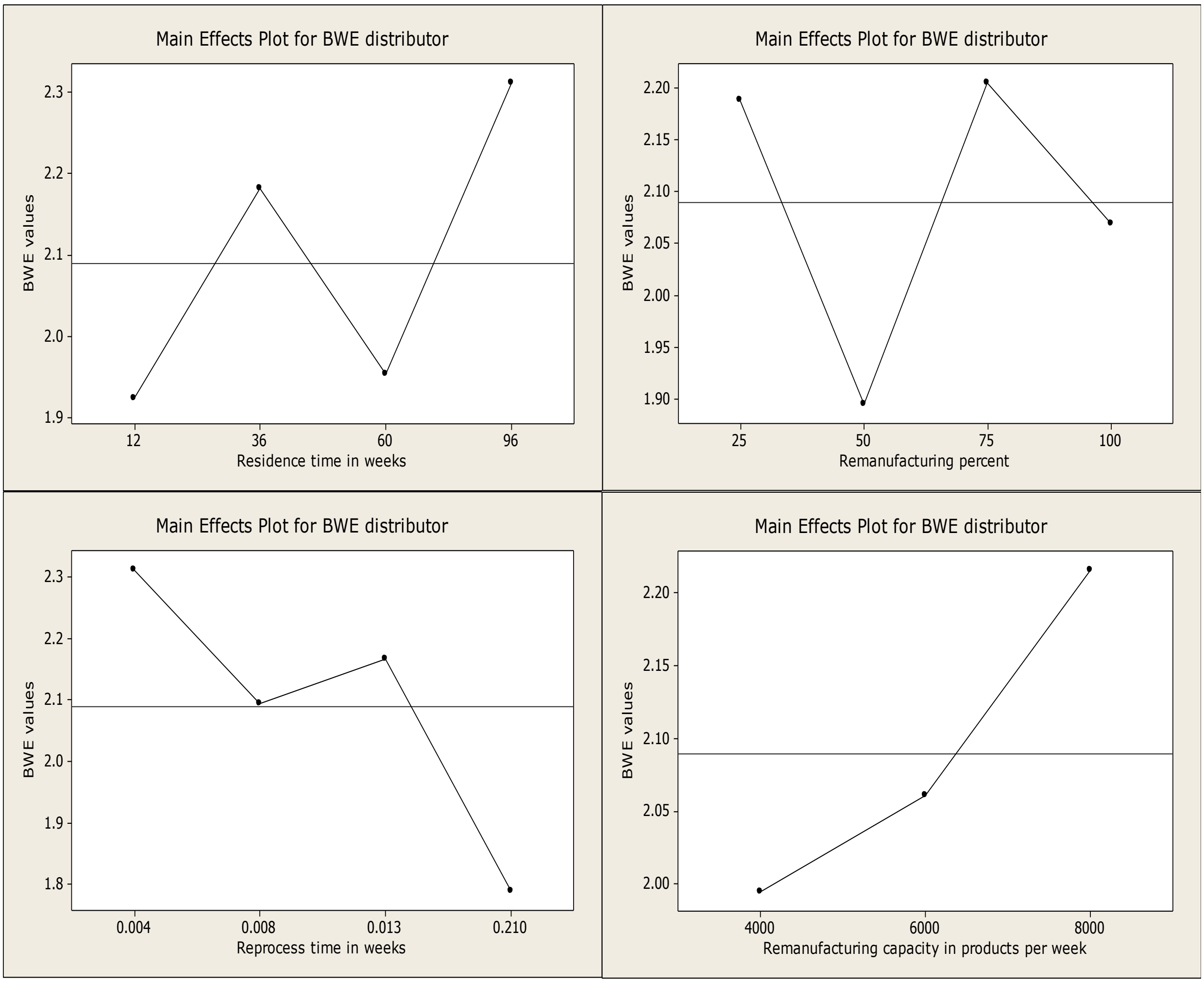


Figure 7.15: Main effects plots for BWE distributor for kitchen appliances with remanufacturing capacity limits only and no external returns

The impact of remanufacturing capacity limits was so strong that it affected how the other factors impacted the BWE distributor. This was different from the electric vehicle batteries. This means that the product demand size and speed did have an impact on the way remanufacturing capacity limits affected the BWE distributor.

BWE wholesaler

The BWE wholesaler behaved in a similar way to the BWE distributor. The variable increased with an increase in remanufacturing capacity limits. The other factors were strongly affected by the presence of the remanufacturing capacity limits and showed no distinctive patterns.

BWE retailer

Table 7.21 shows the significance test for the BWE retailer.

Table 7.21: Significance test for the BWE retailer for kitchen appliances with remanufacturing capacity limits only and no external returns

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	0.267324	0.267604	0.089201	21.85	0.000
Remanufacturing percent	3	0.003081	0.003149	0.001050	0.26	0.856
Reprocess time	3	0.023948	0.024031	0.008010	1.96	0.121
Remanufacturing capacity	2	0.003271	0.003271	0.001636	0.40	0.671
Error	180	0.734931	0.734931	0.004083		
Total	191	1.032556				

In the case of the BWE retailer, the residence time was the only significant factor. The variable increased with an increase in the residence time. The BWE retailer showed no response to the remanufacturing capacity limits. The main effects plot shown in Figure 7.16 shows a decreasing trend for the BWE retailer with increasing remanufacturing capacity. However, the significance test in Table 7.21 shows that the remanufacturing capacity had no significant impact on the BWE retailer, only the residence time did. This meant that the remanufacturing capacity had no impact at all on the BWE retailer.

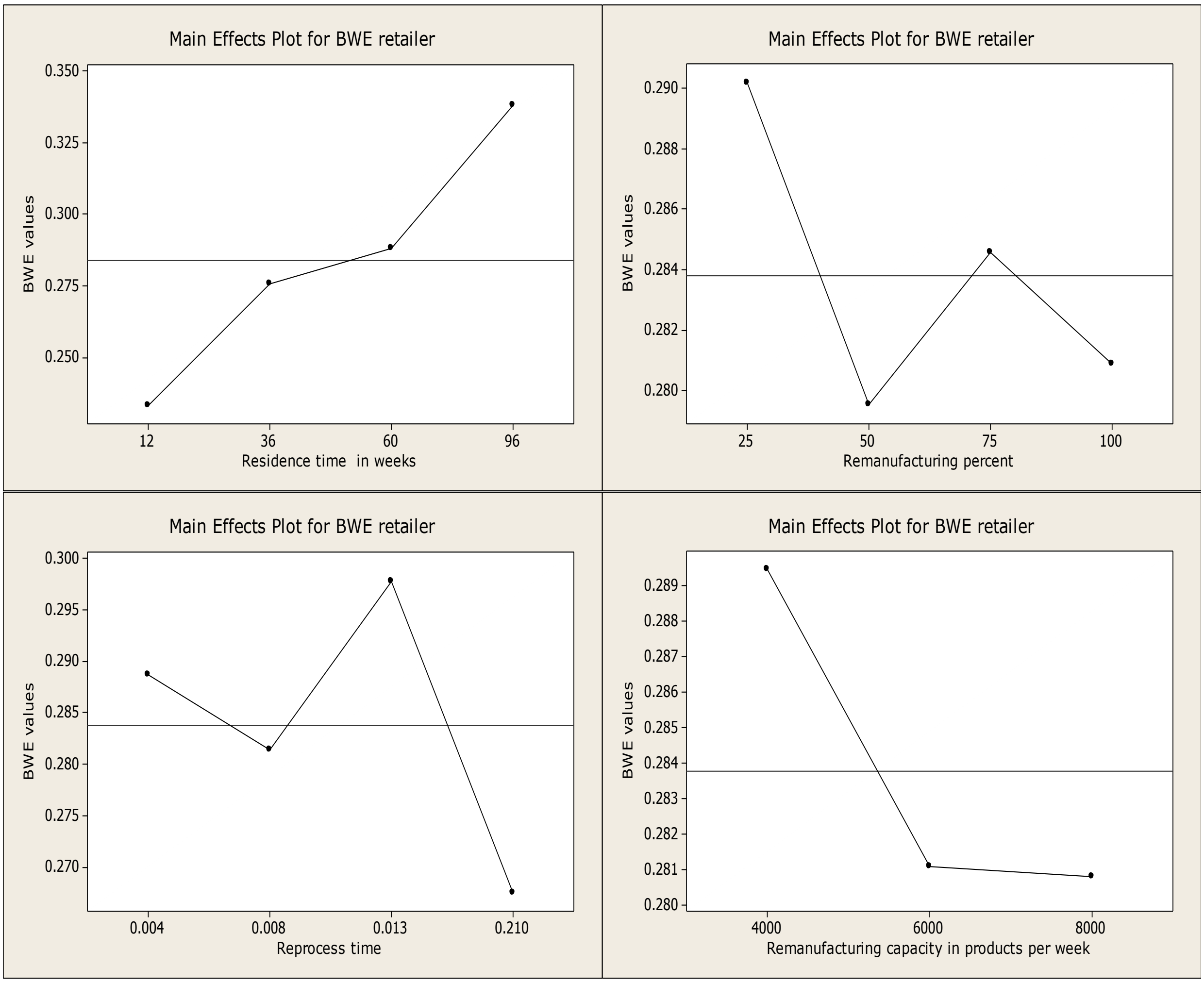


Figure 7.16: Main effects plot for BWE retailer for kitchen appliances with remanufacturing capacity limits and no external returns

The results indicated that for the kitchen appliances, the remanufacturing capacity limits impacted the BWE distributor and the BWE wholesaler but they had no impact on the BWE retailer. The BWE retailer was distinctly affected by the residence time only. The BWE retailer increased with an increase in residence time.

7.5.4 Comparison of results for electric vehicle batteries and kitchen appliances

The introduction of remanufacturing capacity limits to the closed-loop system led to an increase in BWE values compared to the closed-loop system with no capacity limits for both products. BWE values for the closed-loop system with remanufacturing limits only were similar to those of the closed-loop system with collection capacity limits only for both products. The following differences in how the products reacted to remanufacturing capacity limits were noted:

- Although the remanufacturing capacity limits did not show parallel lines in the main effects plots for the electric vehicle batteries, they showed no distinct pattern and the significant tests showed that their impact was insignificant to the BWE at all levels of the closed-loop system. The remanufacturing capacity limits also had no impact on how the other factors affected the BWE at all echelons.

- For the kitchen appliances, the remanufacturing capacity limits had an impact on how the other factors affected the BWE distributor and the BWE wholesaler. The BWE distributor and the BWE wholesaler increased as the remanufacturing capacity limits increased. This was because of the increase in downtime for remanufacturing as well as backlogs for remanufacturing. However, the remanufacturing capacity limits had no impact on the BWE retailer.

7.6 The closed-loop system with both collection and remanufacturing capacity limits

In the last scenario, both collection and remanufacturing capacities were introduced to the closed-loop system of the two products. The experimental plan for this scenario is shown in Figure 7.17.

7.6.1 Poisson distribution for electric vehicle batteries with collection and remanufacturing capacity limits

The parameters of interest for the electric vehicles in the last scenario are shown in Table 7.22.

Table 7.22: Parameters for electric vehicles with both collection and remanufacturing capacity limits

Parameter	Level 1	Level 2	Level 3	Level 4
Remanufacturing percentage	25	50	75	100
Residence time	4 weeks	8 weeks	16 weeks	24 weeks
Reprocessing time	12 hours	15 hours	18 hours	24 hours
Collection capacity	65	75	80	-
Remanufacturing capacity	65	75	80	-

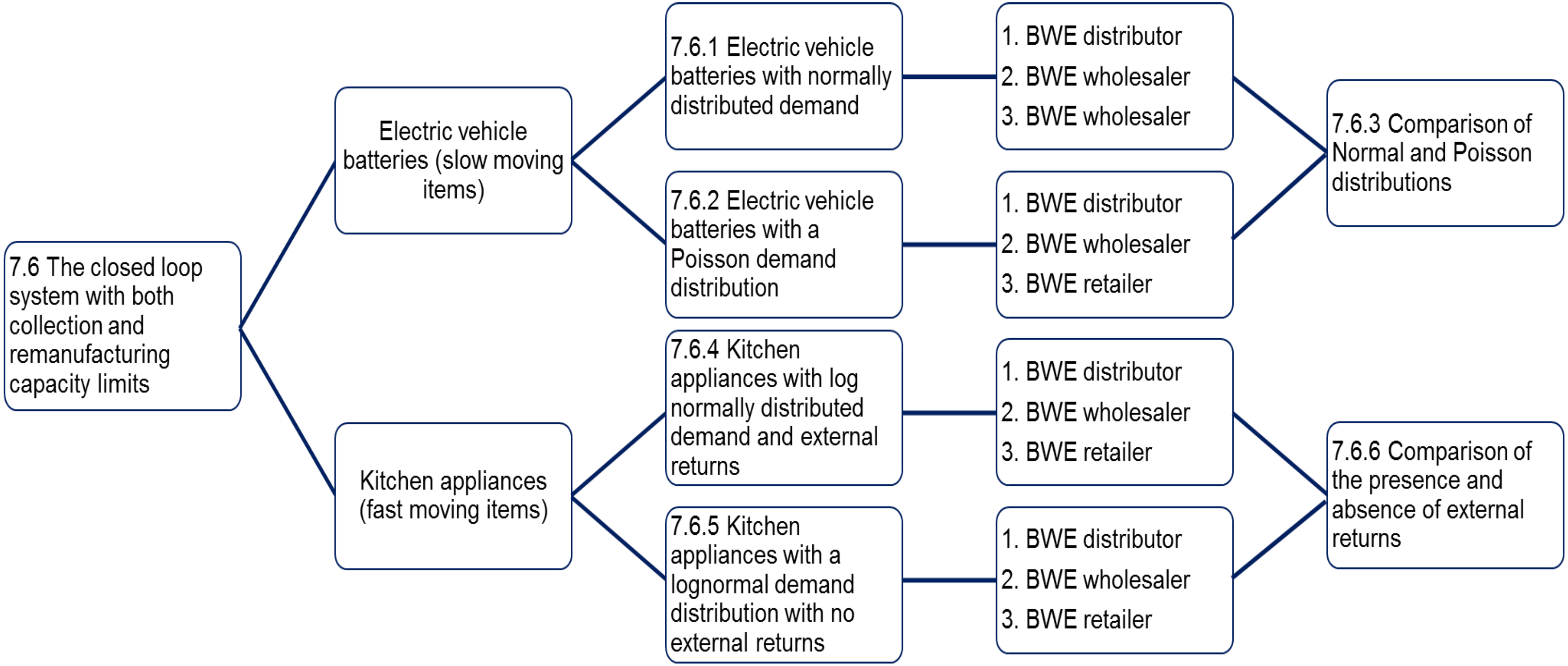


Figure 7.17: Experimental plan for the closed-loop system with both collection and remanufacturing capacity limits

Descriptive statistics

The first observation was the sharp decrease in descriptive statistics for the BWE at all three levels of the supply chain. This is shown in Figure 7.18.

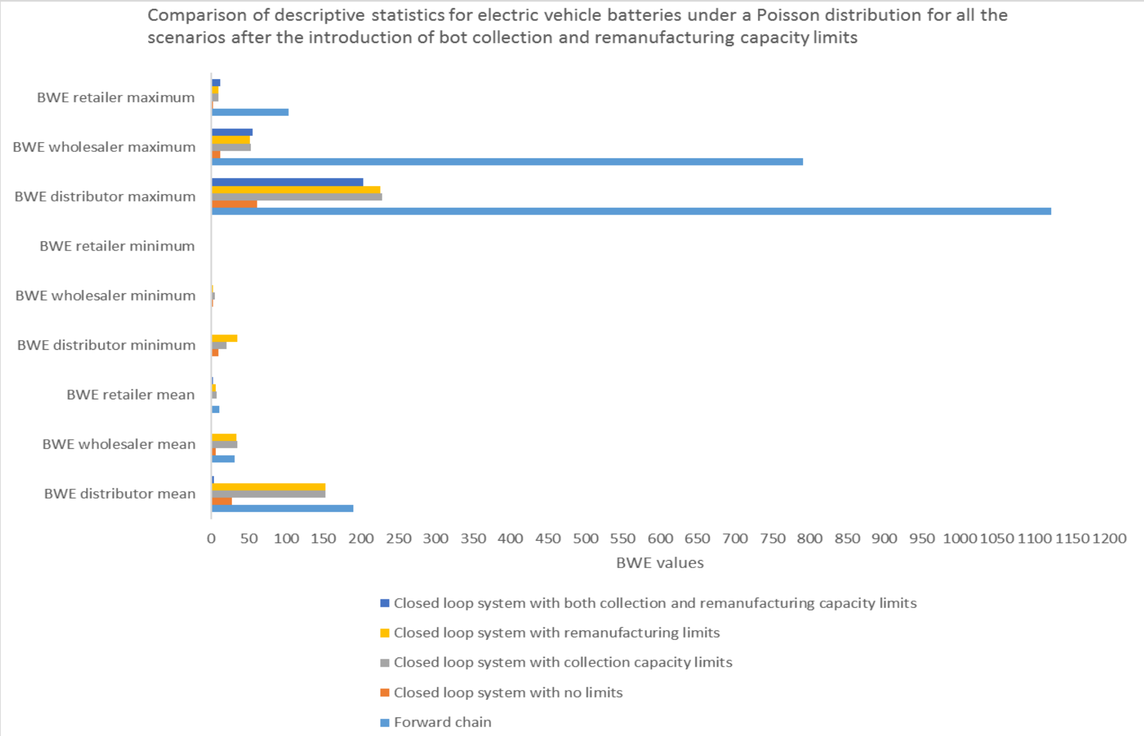


Figure 7.18: Comparison of descriptive statistics for electric vehicle batteries under a Poisson distribution for all scenarios after the introduction of both collection and remanufacturing capacity limits

The BWE values for the closed-loop system with both collection and remanufacturing capacity limits were lower than those for the closed-loop system with collection capacity limits only and those for the closed-loop system with remanufacturing capacity limits only. Similar to the other scenarios, the forward chain had the highest BWE values and the closed-loop system with no capacity limits had the lowest BWE values. Again, the conclusion that introducing capacity limits to the closed-loop system increased BWE values still held.

BWE distributor

With the introduction of both collection and remanufacturing capacity limits, the BWE showed mixed patterns of responses to the residence time, remanufacturing percent and the reprocessing time. The BWE distributor was affected only by the collection and remanufacturing capacities as indicated by the significance tests in Table 7.23.

The BWE distributor also showed a different reaction to collection capacity limits as to scenario 2 when there were only collection capacity limits in the supply chain. Figure 7.19 shows a main effects plot of the BWE distributor after the introduction of both collection and remanufacturing capacity limits.

Table 7.23: Significance tests for the BWE distributor for electric vehicle batteries with both collection and remanufacturing capacity limits

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	291.5	289.0	96.3	0.74	0.528
Remanufacturing percent	3	275.8	281.5	93.8	0.72	0.540
Reprocess time	3	269.9	265.0	88.3	0.68	0.565
Collection capacity	2	484.5	500.3	250.1	1.92	0.014
Remanufacturing capacity	2	167.6	167.6	83.8	0.64	0.012
Error	562	73125.9	73125.9	130.1		
Total	575	74615.2	74615.2			

It can be seen in Figure 7.19 that in the presence of both collection and remanufacturing capacity limits, all the other factors have mixed impact on the BWE distributor. This is because the lines are not horizontal, and this indicates that the means of the factors are different. Although the lines are not horizontal, there are no distinguished patterns as to how these factors impact the BWE distributor in the presence of both collection and remanufacturing capacity limits.

The BWE distributor decreased with an increase in collection capacity in the presence of both collection and remanufacturing capacity. This was a different result from when there were collection capacity limits only. In the presence of both collection and remanufacturing capacity limits, the BWE at all levels increased with increases in remanufacturing capacity limits. This was different from when the remanufacturing capacity limits existed alone in the closed-loop system. This means that in the presence of both collection and remanufacturing capacity limits, it is better to collect more products at a lower remanufacturing capacity than to collect less products at a higher remanufacturing capacity. It should be noted that an increase in remanufacturing capacity also meant an increase in the number of products that had to be collected before remanufacturing can actually take place. Collecting fewer products than the required capacity meant some downtime for remanufacturing. In this instance, it was better to collect more products than the remanufacturing capacity and store them as backlogs than to collect less products and experience both backlogs and downtime for remanufacturing.

BWE wholesaler

The BWE wholesaler behaved in the same way as the BWE distributor, only responding to collection and remanufacturing capacity limits. Similar main effects plots were obtained with similar patterns to that of the BWE distributor.

BWE retailer

The BWE retailer behaved in a similar way to the BWE distributor and the BWE wholesaler.

As a way of verifying if the demand distribution does have an impact in the presence of both collection and remanufacturing limits, the same simulations were run with the electric vehicle data modelled as a normal distribution. For this instance, the normal distribution did have a different reaction to the Poisson distribution. This showed that the demand distribution did have an impact in the presence of both collection and remanufacturing capacity limits.

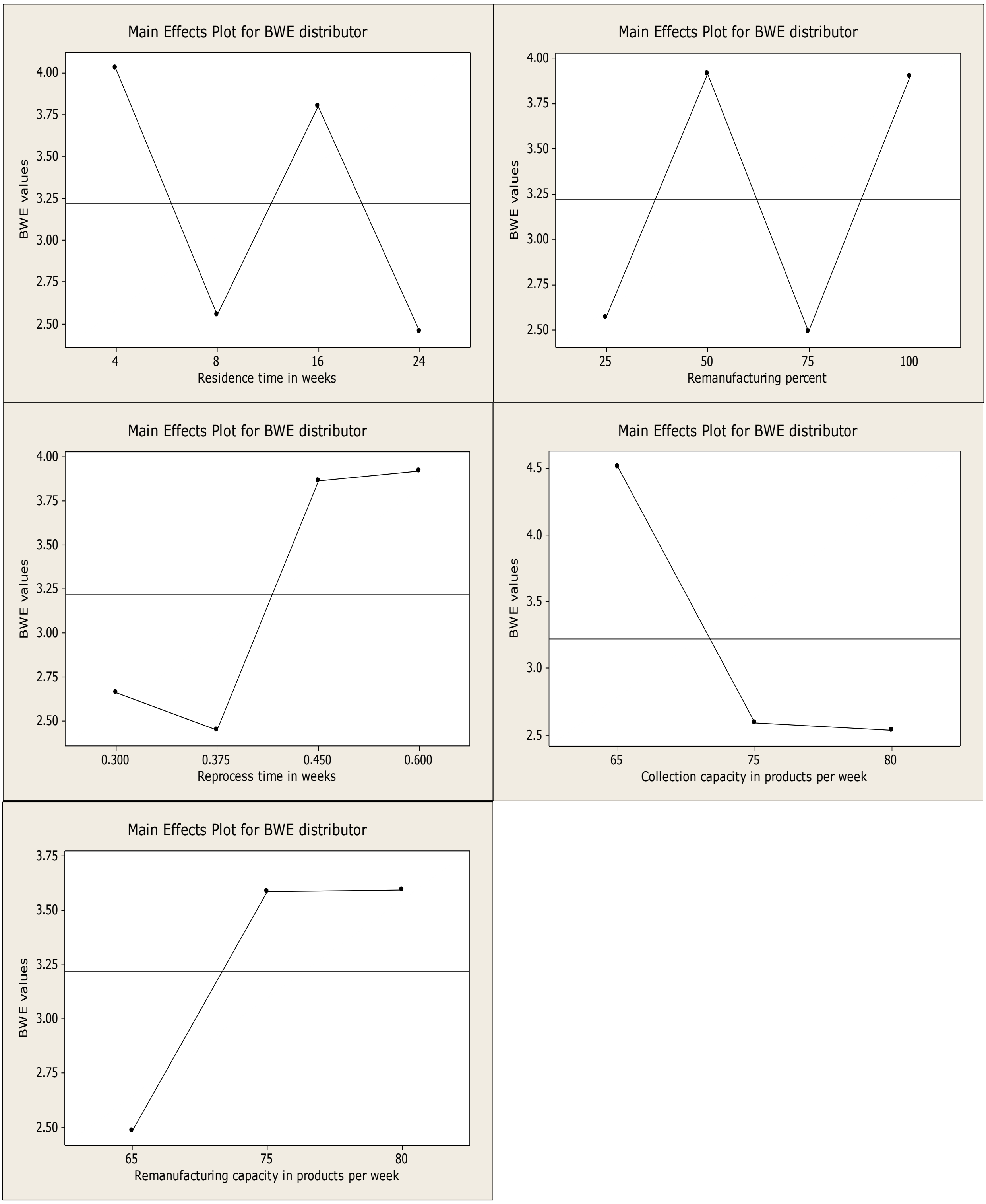


Figure 7.19: Main effects plot for BWE distributor for electric vehicle batteries under a Poisson demand distribution with both collection and remanufacturing capacity limits

7.6.2 Normal distribution for electric vehicle batteries with collection and remanufacturing capacity limits

For the normal distribution of demand, the BWE values decreased with an increase in collection capacity limits and increased with an increase in remanufacturing capacity limits. This was a similar result to the Poisson distribution.

7.6.3 Lognormal distribution for kitchen appliances with collection and remanufacturing capacity limits with external returns

The parameters for the kitchen appliances are shown in Table 7.24

Table 7.24: Parameters for the kitchen appliances with both collection and remanufacturing limits

Parameter	Level 1	Level 2	Level 3	Level 4
Remanufacturing percentage	25	50	75	100
Residence time	12 weeks	36 weeks	60 weeks	96 weeks
Reprocessing time	30minutes	60 minutes	100minutes	130 minutes
Collection capacity	4000 products/week	6000 products/week	8000 products/week	-
Remanufacturing capacity	4000 products/week	6000 products/week	8000 products/week	-

The presence of external returns did not show any distinct patterns on how the factors had an impact on the BWE in the closed-loop system. For this reason, the simulations were run again without external returns.

7.6.4 Lognormal distribution for kitchen appliances with collection and remanufacturing capacity limits without external returns

Descriptive statistics

After introducing collection and remanufacturing capacity limits, a comparison of descriptive statistics was made. The comparison included BWE values for the forward chain with no returns, the closed-loop system with co-capacity limits, the closed-loop system with collection capacity limits only and the closed-loop system with both collection and remanufacturing capacity limits. This comparison is visualised in Figure 7.20.

Introducing both collection and remanufacturing capacity limits increased the BWE at all values of the closed-loop system. From Figure 7.20, the closed-loop system with both collection and remanufacturing capacity limits has larger BWE values than the closed-loop system with no capacity limits, the closed-loop system with collection capacity limits only and the closed-loop system with remanufacturing capacity limits only. This means that the conclusion that introducing capacity limits increases the BWE still holds. However, even in the presence of capacity limits, the closed-loop system still has lower BWE values than the forward chain without any returns. This also means that introducing product returns does reduce the BWE in a supply chain. The kitchen appliances responded to the presence of both collection and remanufacturing capacity limits in a different way from the electric vehicle batteries. This means that the size of the demand had an impact on how the closed-loop system responded to the presence of both the collection and remanufacturing capacity limits.

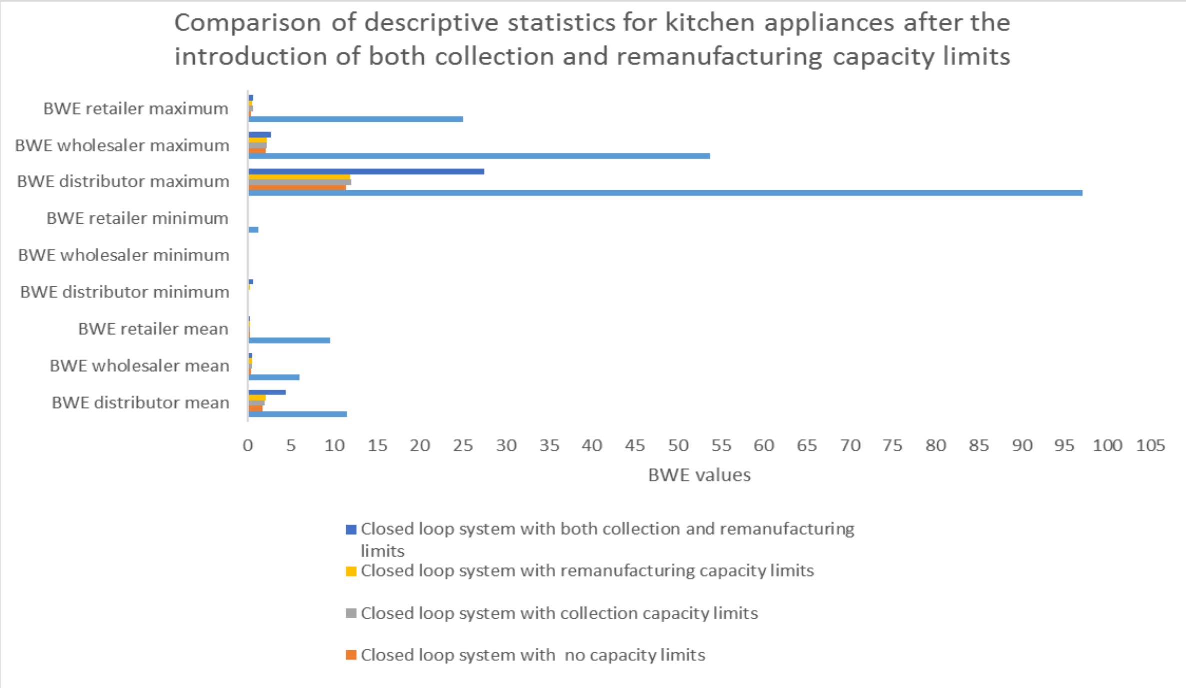


Figure 7.20: Comparison of descriptive statistics for kitchen appliances after the introduction of both collection and remanufacturing capacity limits

BWE distributor

The test for significance of factors for the BWE distributor is shown in Table 7.25. In the presence of both collection and remanufacturing capacity limits, some factors became insignificant. The only significant factors were the residence time and the remanufacturing capacity.

Table 7.25: Significance tests for the BWE distributor for kitchen appliances with both collection and remanufacturing capacity limits

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	232.90	234.91	78.30	5.66	0.001
Remanufacturing percent	3	10.12	9.05	3.02	0.22	0.884
Reprocess time	3	8.29	8.89	2.96	0.21	0.886
Collection capacity	3	25.40	22.09	7.36	0.53	0.661
Remanufacturing capacity	2	100.60	100.60	50.30	3.63	0.029
Error	135	1868.55	1868.55	13.84		
Total	149	2245.87				

In the presence of collection and remanufacturing capacity limits, the BWE distributor increased with an increase with residence time. The remanufacturing percentage and the reprocessing time had no distinct pattern and they were almost horizontal, showing that the factors had no impact on the BWE in the closed-loop system. This is shown by the main effects plots in Figure 7.21.

The BWE distributor showed no distinct pattern of reaction to collection capacity limits in the presence of both collection and remanufacturing capacity limits. However, the variable decreased with an increase in remanufacturing limits. This was different from the reaction in the presence of the remanufacturing capacity limits only. In this instance, it was better to have more downtime and backlogs resulting from high remanufacturing capacities than to collect more products with less remanufacturing capacities.

BWE wholesaler

The BWE wholesaler behaved in a similar manner to the BWE distributor in the presence of both collection and remanufacturing capacity limits.

BWE retailer

The BWE retailer increased with an increase in collection capacity limits. The same variable also decreased with an increase in remanufacturing capacity limits. This again was a different result from when the collection and remanufacturing capacity limits stood alone. The BWE retailer showed that it is better to collect less products with higher remanufacturing limits than to collect more products with lower remanufacturing limits.

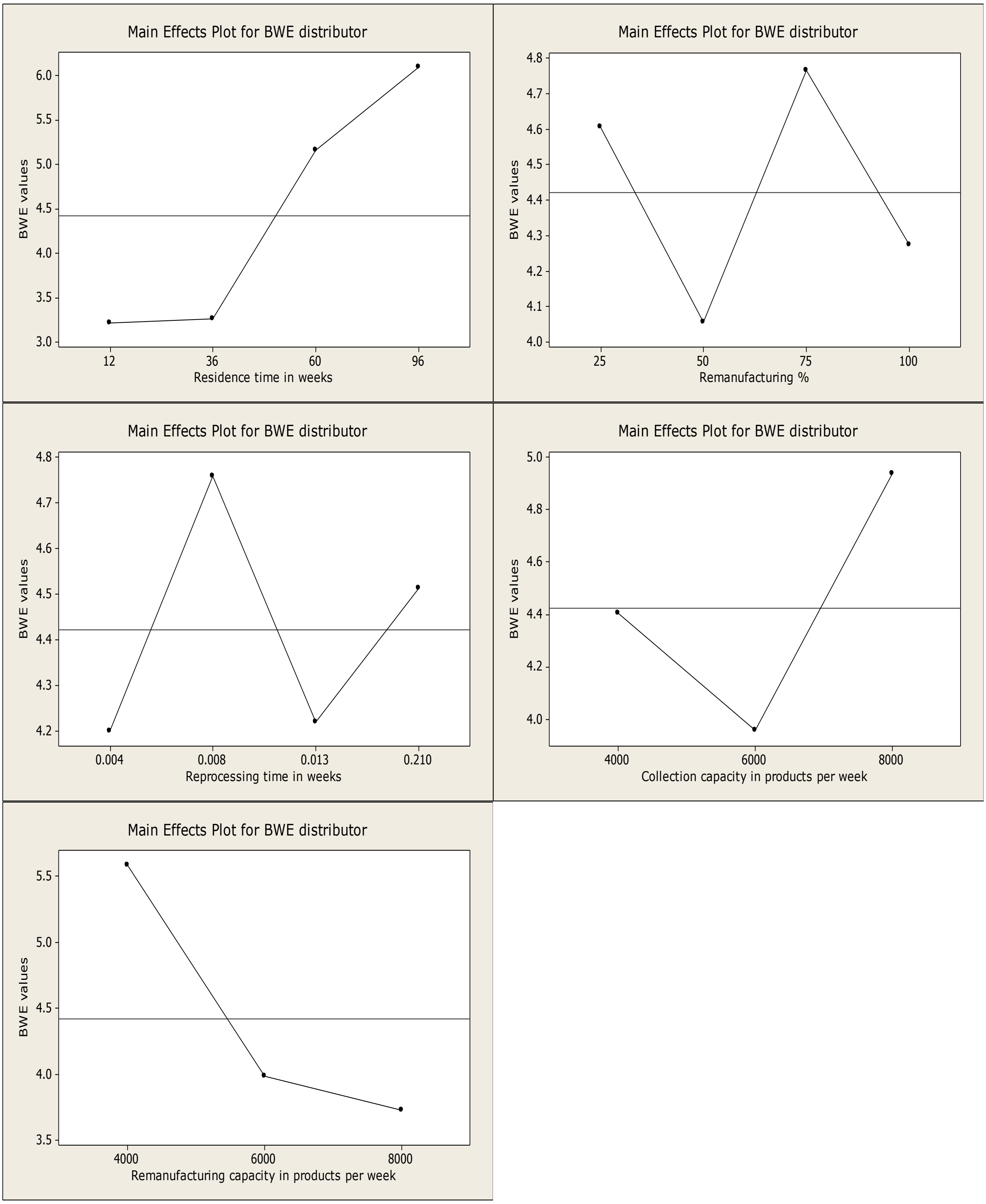


Figure 7.21: Main effects plot for BWE distributor for kitchen appliances with both collection and remanufacturing capacity limits

7.6.6 Comparison of the results obtained from the kitchen appliances and the electric vehicle batteries

The introduction of both collection and remanufacturing capacity limits to both products brought about completely different results with no common ground. These results are summarised by using the following points:

- With the introduction of both collection and remanufacturing capacity limits for the electric vehicles, all other factors were affected and the only significant factors were the collection and remanufacturing capacity limits for the BWE values at all levels.
- For the electric vehicle batteries, the BWE values at all levels increased with an increase in remanufacturing capacity limits and decreased with increasing collection capacity limits. This means that, for the electric vehicle batteries, it was better to collect more products and stock them as backlogs than to collect less products and have remanufacturing downtime as well as backlogs.
- For the kitchen appliances, introducing both collection and remanufacturing capacity limits also affected the performance of other factors except the residence time. For the BWE distributor and the BWE wholesaler, the only significant factors were the residence time and the remanufacturing capacity limits. For the BWE retailer, the significant factors were the residence time, the collection capacity and the remanufacturing capacity.
- The BWE at all levels decreased with an increase in remanufacturing capacity for the kitchen appliances. This means that it was better to collect less products and risk downtime than to collect and stock more products as backlogs for the kitchen appliances.

This difference in results demonstrated that the demand size and the speed of the items did have an impact on how the closed-loop systems reacted to capacity constraints.

7.7 Conclusion

This chapter carried out the case study and scenario experimentation of the research. The chapter carried out experiments based on the hypotheses listed in Chapter 1. The results from the case study and scenario experimentation in this chapter will be used in deriving the managerial implications explained in Chapter 8. The general observation was that the introduction of capacity limits leads to an increase in the BWE in a closed-loop system and how the values of the capacity limits affected the BWE depended on the size and speed of the demand of a product. These conclusions were based on the two cases described in Chapter 6 of electric vehicle batteries and kitchen appliances. Chapter 8 will explain the results, findings and the managerial implications of the analysis of the simulation.

CHAPTER 8
FINDINGS, CONCLUSIONS AND MANAGERIAL IMPLICATIONS

This chapter highlights the key findings and managerial implications from the experimental results obtained from the previous chapter. It first explains the findings and implications obtained from the forward chain experimentation, followed by the findings and managerial implications of certain reverse logistics decisions on the stability and performance of the closed-loop system as measured by the BWE.

8.1 The forward chain with no product returns

Table 8.1 summarises the results from the forward chain with no product returns. The results agreed with those of Das and Dutta (2013). The main findings were that;

1. An increase in inventory adjustment time led to a decrease in the BWE at all levels of the supply chain.
2. An increase in the inventory cover time led to an increase in the BWE at all levels of the supply chain.
3. Factors on the downstream levels of the supply chain had an impact on the BWE of the upstream levels. However, factors on the upstream levels of the supply chain had no impact at all on the BWE of the downstream levels.
4. The conclusion that the BWE increases as one goes upstream held in all cases.
5. The demand distribution had no impact on how the factors affected the BWE in a supply chain.

These results from the forward chain are explained in the following subsections.

8.1.1 Impact of inventory adjustment time

Key Findings

The inventory adjustment time was described as the time it takes for an echelon to adjust inventory in response to changes in demand. Adjusting discrepancies in inventory levels too quickly led to an increase in BWE at all levels as the order variation increased, hence a decrease in the inventory adjustment time led to an increase in the BWE at all levels.

Managerial implications

From the operational perspective, it is more beneficial to the supply chain players to make allowances for inventories to take time to absorb demand variances. This is preferable to quickly adjusting production and distribution to match the variable demand. Taking time and giving inventories time to absorb demand changes resulted in lower BWE in the supply chain at all levels.

Table 8.1: Summary of forward chain results

	Results for electric vehicle batteries						Results for kitchen appliances					
	Normal distribution			Poisson distribution			Normal distribution			Lognormal distribution		
Parameter	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer
Retailer inventory adjustment time↑	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
Retailer inventory cover time↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Wholesaler inventory adjustment time↑	↓	↓	No impact	↓	↓	No impact	↓	↓	No impact	↓	↓	No impact
Wholesaler inventory cover time↑	↑	↑	No impact	↑	↑	No impact	↑	↑	No impact	↑	↑	No impact
Distributor inventory adjustment time↑	↓	No impact	No impact	↓	No impact	No impact	↓	No impact	No impact	↓	No impact	No impact
Distributor inventory cover time↑	↑	No impact		↑	No impact	No impact	↑	No impact	No impact	↑	No impact	No impact

Key

↑ - An increase in a parameter or variable

↓ -a decrease in a parameter or variable

8.1.2 Impact of inventory cover time

Key Findings

The inventory cover time was defined as a level of safety stock kept as a cushion against variabilities in demand. Lin, Jiang, and Wang (2014) defined the inventory cover time as, "the summation of minimum order processing time and safety stock coverage". This meant that increasing the order processing time and the safety stock increased this parameter. From the formulation of the model, the desired inventory at each stage was obtained by multiplying the demand forecasts with the inventory cover time. An increase in this factor meant a multiplicative increase in the desired inventory at each echelon and larger orders placed by that echelon. This led to an increase in the BWE at each echelon.

Managerial implications

It is necessary for managers to consider reducing the time taken to process order and the safety stock (inventory cover time). This time affects the desired inventory level in a periodic review policy. An increase in the desired inventory level would mean larger orders placed by each echelon relative to the actual orders placed by the customer. This led to increases in oscillations in the supply chain as measured by the BWE. Managers should take care in selecting safety stock levels and they should ensure an efficient order processing system to minimise the cover time.

8.2 The closed-loop system with no capacity limits

In the reverse chain with no capacity limits the following was observed;

1. The BWE at all levels of the supply chain decreased with an introduction of product returns. This was in agreement with Das and Dutta (2013) as well as the conclusions reached by Zhou and Disney (2006).
2. The very small reprocessing time (that was small in comparison to the residence time) had no significant impact on the BWE at all levels for both product types.
3. For kitchen appliances, the presence of external returns affected how the factors under investigation impacted the BWE in the closed-loop system.
4. The BWE at all levels for the electronic vehicle batteries first increased and then decreased with an increase in remanufacturing percentage.

Table 8.2 summarises how the factors had an impact on the BWE in the closed-loop system. The results from the reverse chain without capacity limits are explained in the following subsections.

Table 8.2: Summary of results for the closed-loop system with no capacity limits

	Results for electric vehicle batteries						Results for kitchen appliances					
	Normal distribution			Poisson distribution			Normal distribution			Lognormal distribution		
Parameter	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer
Residence time↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Remanufacturing percentage↑	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
External returns	N/A	N/A	N/A	N/A	N/A	N/A	↓	↓	↓	↓	↓	↓
Reprocessing time↑	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact

8.2.1 Impact of introducing product returns in the supply chain

Key Findings

Introducing product returns in the supply chain reduced the BWE. The BWE further reduced as the yield from the returns increased (remanufacturing percentage). This was because increasing the return rate improved the availability of material in the supply chain. The availability of material in the supply chain reduced the levels of stock-outs. This lowered the impact of variabilities in the supply chain and hence the BWE in the supply chain.

However, for low demand items (electric vehicle batteries) increasing the return yield from 25% to 50% increased the BWE then it decreased after 50%. This showed that increasing the return yield does not always reduce the BWE for all product types and it does have a limit to which it reduces the BWE effect.

Managerial implications

Introducing product returns in a supply chain for remanufacturing is a good way of not only protecting the environment but recovering some expensive material that can be reused to produce other products. This is a good practice for environmental sustainability. However, introducing a reverse chain may complicate operations as there are uncertainties in the quality, quantity and timing of returns.

Even though product returns complicate the supply chain, they also improve the dynamics of the supply chain as they reduce the BWE at all levels. Managers are encouraged to incorporate reverse chains into their supply chains whenever possible and not just for sustainability.

8.2.2 Impact of the remanufacturing lead time (residence time and reprocessing time)

Key Findings

The reprocessing time demonstrated no impact at all in the supply chain because it was too small in comparison to the residence time for both product types. However, increasing the residence time increased the BWE at all stages of the supply chain.

The results agreed with those of Zhou, Naim, and Disney (2017). The authors argue that the time that the product spent in the market place tended to reflect the macro environment beyond the closed-loop system itself and a shorter time was more preferable. The authors argue that a shorter residence time results in less overshoot and undershoot and this leads to less response times. According to the authors, quick response times produce a system with less inertia. Cannella, Bruccoleri, and Framinan (2016) showed that the time compression principle should be extended to remanufacturing processes as well.

Managerial implications

It is necessary to reduce the time that the customer keeps the product before returning it. This did not depend on product type. It applied to both products under study. According to Zhou et al.(2017), returning products early means better quality products and this leads to more return yield and less reprocessing time for returns.

In order to reduce the BWE in closed-loop systems, managers are encouraged to find ways to encourage customers to return products earlier. They can offer incentives depending on the quality of product returned. Better quality reduces the time taken to reprocess products and this will reduce the remanufacturing lead time and hence the BWE.

However, for the products under study, the reprocess time was too small as compared to the residence time, so in this case strategies have to be put in place to focus more on reducing the residence time. Examples of such strategies include product exchange policies mentioned by Das and Dutta (2013) whereby customers are paid more for better quality products.

8.2.3 Impact of the presence of external returns in a closed-loop system

Key Findings

The presence of external returns in the supply chain for kitchen appliances led to a decrease in the BWE at all levels. However, the presence of external returns also affected how the BWE in the closed-loop system was impacted by the other factors under investigation. This was because the external returns were not regulated by the organisation. Their return was continuous and they had no delays such as residence time. Even when the company collected no products of its own, there were always returns in the system coming from external sources. This made the impact of remanufacturing percentage and residence time of the company's own products insignificant.

Managerial implications

Managers should not ignore the presence of external returns in the supply chain. Closed-loop systems with returns from external sources added to returns of their own products have more complex supply chain dynamics. The external returns not only affect the BWE in the supply chain but they also affect how other factors in the closed-loop system affect supply chain dynamics.

8.3 The closed-loop system with collection capacity limits only

The main observations from this scenario are listed;

1. With the introduction of product returns and collection capacity limits, the BWE at all levels of the supply chain increased for both products.
2. The two products showed differences in response to the introduction of collection capacity limits into the supply chain. For the electric vehicles, in the presence of collection capacity limits, the BWE at all levels increased with an increase in remanufacturing percentage, residence time and collection capacity limits. This was different from the kitchen appliances. For the kitchen appliances, the BWE at all levels increased with an increase in residence time but it decreased with an increase in collection capacity limits.

The following subsections explain these findings. The impact of the factors under investigation under this scenario is summarised in Table 8.3.

Table 8.3: Summary of results for the closed-loop system with collection capacity limits only

	Results for electric vehicle batteries						Results for kitchen appliances					
	Normal distribution			Poisson distribution			Normal distribution			Lognormal distribution		
Parameter	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer
Residence time↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Reman %↑	↑	↑	↑	↑	↑	↑	No impact	No impact	No impact	No impact	No impact	No impact
Reprocessing time↑	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact
Collection capacity limits↑	↑	↑	↑	↑	↑	↑	↓	↓	↓	↓	↓	↓

8.3.1 Impact of the introduction of collection capacity limits

Key Findings

When collection capacity limits where introduced to the closed-loop system, the BWE increased for both products. This was because not all products were being directly absorbed into the remanufacturing process. This meant that the availability of material was also limited and chances of stock-outs and the BWE increased.

However, for the electric vehicle batteries, when collection capacity limits were introduced, they not only impacted the BWE but they also had an impact on how the other factors affected the BWE. Before the introduction of collection capacity limits, the BWE at all levels for electric vehicle batteries decreased with an increase in remanufacturing percentage. The opposite was true when collection capacity limits were introduced. The BWE for these products also increased with an increase in the collection capacity limits. This meant that in the presence of collection capacity limits, the BWE for the electric vehicle batteries increased as more products were collected and remanufactured, i.e. the BWE increased with an increase in return yield. In this case, the results agreed with those of Ding and Gan (2009). This different response shown by the electric vehicle batteries could have been because of the size of the demand. The electric vehicle batteries had an average demand of 80 units per week. The results showed that it was in the best interests of the organisation to have the minimum collection capacity limits.

As a result of these different responses, it can be argued that collection capacity limits do have an impact on the BWE in a closed-loop system, but how a product's closed-loop system reacts to collection capacity limits depends on the size of its demand. For low demand and slow moving items (electric vehicle batteries), increasing the collection capacity limits increased the BWE at all levels. In a different way, increasing the collection capacity limits for kitchen appliances with a high and fast demand decreased the BWE at all levels of the supply chain.

Managerial implications

The research has proved beyond doubt that collection capacity limits do have an impact on the BWE in closed-loop systems- they limit the amount of products available for remanufacturing which increases the BWE. However, in considering capacity expansion policies such as outsourcing, managers should consider the size of the demand and the speed at which the product type disappears from the shelves. This is because expanding collection capacity does not always lower the BWE in a supply chain for all product types. It depends on the demand size. Very low demand items react negatively to an increase in collection capacity limits while high speed high demand items react positively.

8.4 The closed-loop system with remanufacturing capacity limits only

The reaction of the different products to remanufacturing capacity limits was also different for the two case studies. However, unlike the collection capacity limits, the presence of remanufacturing capacity limits did not affect how the other factors impact the BWE in the closed-loop system. The results for this scenario are summarised in Table 8.4.

Table 8.4: Summary of the reverse chain with remanufacturing capacity limits results

	Results for electric vehicle batteries						Results for kitchen appliances					
	Normal distribution			Poisson distribution			Normal distribution			Lognormal distribution		
Parameter	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer
Residence time↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Reman %↑	↓	↓	↓	↓	↓	↓	No impact	No impact	No impact	No impact	No impact	No impact
Reprocessing time↑	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact
remanufacture capacity↑	No impact	No impact	No impact	No impact	No impact	No impact	↑	↑	No impact	↑	↑	No impact

Key Findings

Remanufacturing capacity limits had no impact on the low demand items (electric vehicle batteries) and they behaved in a similar way as they did when there were no capacity limits in the closed-loop system. The BWE at all levels of the supply chain for electric vehicle batteries increased with an increase in residence time and it decreased with an increase in remanufacturing percentage. Despite the fact that the remanufacturing capacity limits came with a condition that allowed for batching of orders and some periods where there was no remanufacturing, in this case they still had no impact. The reaction of the electric vehicle batteries to the presence of remanufacturing capacity limits agreed with the findings of Adenso-Díaz et al. (2012) that the recycler's capacity limits had no impact on the BWE in a closed-loop system.

For the high speed, high demand items, the remanufacturing capacity limits did have an impact. The remanufacturing capacity limits had a condition that when the products collected were less than the remanufacturing capacity, then there was no remanufacturing in that period and there were backlogs in remanufacturing. This allowed for batching of remanufacturing orders. In the case of the kitchen appliances, the BWE at the distributor and the wholesaler increased as the remanufacturing capacity limits were increased. This was because increasing remanufacturing capacity limits meant increasing the number of products that have to be collected before remanufacturing can actually take place. In this case if the company failed to collect enough products in a certain period, then there was downtime for remanufacturing and also an increase in backlogs for remanufacturing. This was because when the collected products were not enough for remanufacturing, they were not remanufactured but stocked until there were enough. This led to delays in material flow and increased the BWE.

The remanufacturing capacity limits had no impact on the BWE at the retailer level, although the conclusion that the BWE increases as one moves upstream still held. The BWE at all levels also increased as the residence time increased and showed no distinct pattern where the remanufacturing percentage was concerned. This was a new finding. This finding again meant that the size and pattern of the demand again had an effect on how the closed-loop system reacted to remanufacturing capacity limits.

Managerial implications

The size and pattern of the demand has to be considered when considering remanufacturing capacity expansion policies. For low demand items, increasing the remanufacturing capacities where remanufacturing only begins when enough products have been collected (i.e. no remanufacturing takes place when the collected products are less than the remanufacturing capacity), has no impact on the BWE and the dynamics of the system. However, it will increase backlogs in remanufacturing.

For high demand and high speed items like kitchen appliances, increasing the remanufacturing capacity limits where remanufacturing begins only when enough products have been collected, increases the BWE in the supply chain and care should be taken when considering capacity expansion policies for plants operating at full capacity.

8.5 The closed-loop system with both collection and remanufacturing capacity limits

The last scenario of the dissertation involved adding both collection and remanufacturing capacity limits to the closed-loop system. In the presence of both collection and remanufacturing capacity limits, both product types showed different reactions to both collection and remanufacturing capacity limits from the previous scenarios. The results are summarised in Table 8.5.

Key findings for electric vehicle batteries

Introducing both collection and remanufacturing capacity limits to the electric vehicle batteries led to a sharp decrease in BWE at all stages.

The electric vehicle batteries' BWE increased with an increase in remanufacturing capacity limits and decreased with an increase in collection capacity limits. This meant that it was better to collect more products and stock them. The collection capacity should be more than the remanufacturing capacity to minimise downtime of remanufacturing. In this instance, the remanufacturing downtime had more impact on the BWE than the backlogs accrued by collecting more products than can be remanufactured. Collecting products that are more than the remanufacturing capacity is therefore better than collecting products that are less than the remanufacturing capacity, in a situation where an organisation has to collect enough for remanufacturing to take place.

Managerial implications for the electric vehicle batteries (low demand and slow items)

For low demand items, in the presence of both collection and remanufacturing capacity limits and a company that had to collect enough products before remanufacturing begins, it is better to collect more products that are above the remanufacturing capacity than it is to collect less products than the remanufacturing capacity. It is better to have large collection capacities and lower remanufacturing capacities than it is to have lower collection and larger remanufacturing capacities. Having lower remanufacturing capacities when the company has to collect enough products to begin remanufacturing meant that there would be less periods where there is no remanufacturing, due to the batching process. It was better to have less periods of no remanufacturing with remanufacturing backlogs (due to high collection capacities) than to have more periods with no remanufacturing and have less backlogs (due to less collection capacity).

Managers should note that the more periods of no remanufacturing they were, the more unstable the closed-loop system for low demand items became and the greater the BWE in the system. There is a trade-off in this finding. Whilst increasing the remanufacturing capacity limits meant more remanufactured products being introduced back to the forward chain, it also meant more periods of downtime in remanufacturing especially if an organisation had lower collection capacity. This meant that the BWE could be reduced under high remanufacturing capacity limits only when the organisation can match the high remanufacturing capacity limits with high collection capacities.

Table 8.5: Summary of the reverse chain with collection and remanufacturing capacity limits results

	Results for electric vehicle batteries						Results for kitchen appliances					
	Normal distribution			Poisson distribution			Normal distribution			Lognormal distribution		
Parameter	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer	BWE distributor	BWE wholesaler	BWE retailer
Residence time↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Reman %↑	↓	↓	↓	↓	↓	↓	No impact	No impact	No impact	No impact	No impact	No impact
Reprocessing time↑	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact	No impact
Collection capacity↑	↓	↓	↓	↓	↓	↓	↑	↑	↑	↑	↑	↑
remanufacture capacity↑	↑	↑	↑	↑	↑	↑	↓	↓	No impact	↓	↓	No impact

The results of the electric vehicle batteries also demonstrated that if capacity limits should be introduced into the system, then both collection and remanufacturing capacity limits should be introduced and not just one of the two. This is because the BWE had the lowest values when both collection and remanufacturing capacity limits were introduced to the system. The BWE was lower than that of the forward chain on its own, the closed-loop system with collection capacity limits and the closed-loop system with remanufacturing capacity limits. However, the scenario still had higher BWE values than the closed-loop system with no capacity limits.

Key Findings for the kitchen appliances

For the kitchen appliances, the results were different from the electric vehicle batteries. In this case again, the demand size and speed had an impact on how the capacity limits impacted the BWE in the closed-loop system.

For the kitchen appliances, the BWE increased with an increase in collection capacity and decreased with an increase in remanufacturing capacity limits. For kitchen appliances, it was better to have more periods of remanufacturing downtime than it was to collect more products and have more backlogged products for remanufacturing. The system demonstrated that remanufacturing backlogs are better at reducing bullwhip than collection backlogs. The kitchen appliances showed that it is better to delay remanufacturing in the case where the company has to collect enough products for remanufacturing to begin than it is to just collect products and keep them as backlogs waiting to be remanufactured, as this impacted the forecast of the expected remanufactured products within the closed-loop system.

Managerial implications for kitchen appliances

The results demonstrated that for high demand, high speed items, it is better to delay remanufacturing due to a small number of products collected than it is to collect more products and keep them at the remanufacturing stations as remanufacturing backlogs. It is therefore better to have higher remanufacturing capacity than collection capacity. This is because with high remanufacturing capacities, more products were introduced back into the forward chain and this had an impact of reducing the BWE. Another reason was that backlogs affect the forecast of remanufactured products and the stability of the serviceable inventory. In this situation, there was a trade-off between more periods of downtime with high remanufacturing capacity limits and lower BWE. Like the electric vehicles, the kitchen appliances also demonstrated that low BWE values can be achieved under high remanufacturing capacities as long as the company can control its collection to match that of the remanufacturing so that no backlogs can be observed by the system.

8.6 Conclusion

This chapter explained the findings and managerial implications of the different scenarios of the research. The next chapter explained the reflections from the author as well as recommendations to various organisations involved in reverse logistics.

CHAPTER 9
EPILOGUE

This chapter reflects on the overall research journey. The main discussions of this chapter include the thesis overview, research questions and the research approach. The chapter also explains the research contribution, recommendations and suggestions for future research.

9.1 Thesis overview

The research originated from the concept of extending the BWE as explained by Wang and Disney (2015). With research on the BWE in supply chains reaching the avoidance and mitigation phase, there has been evidence that new topics are being merged with BWE studies. The authors mentioned extending the concept of BWE to sustainability issues in their invited review. A literature review revealed that there is not much literature on the BWE in closed-loop supply chains (reverse supply chains). The same literature review showed that for those studies that focused on the BWE in closed-loop systems, almost all of them assumed that there were no capacity limits in the reverse chain and products were remanufactured as they were collected. However, capacity limits do exist in closed-loop systems and authors such as Vlachos, Georgiadis, and Iakovou (2007) investigated organisations operating remanufacturing operations using dynamic capacity and capacity expansion policies.

This dissertation investigated the existence of capacity limits from an operational and technical point of view. The dissertation investigated the impact of having capacity limits in the reverse chain on supply chain dynamics measured by the BWE. The scenarios defined in the dissertation were obtained from situations experienced by remanufacturing organisations as described by Heydari, Govindan, and Jafari (2017). In these situations, a remanufacturing organisation may either: 1. Collect products less than enough for remanufacturing and experience remanufacturing downtime, or 2. collect more than enough products. These two scenarios cause remanufacturing inefficiencies. This dissertation investigated the impact of these scenarios on supply chain dynamics. By considering the assumption made by the majority of authors that the remanufacturing capacity is unlimited, this dissertation not only provided a realistic view of the remanufacturing process but it also filled a gap in literature.

In carrying out this research, the dissertation used two real case studies in the remanufacturing sector and this made the research more empirical. Data from these case studies was used to model the base case scenarios of the systems dynamics simulation used for modelling closed-loop systems. The existence of collection and remanufacturing capacity limits was investigated from a systems dynamics point of view with an aim to investigate how supply chain dynamics (measured by the BWE) are affected by the presence of these capacity limitations in the closed-loop system. The choice of the systems dynamics methodology and simulation was inspired by its successful application by various researchers (Sy, 2017; Das and Dutta, 2013 and (Adenso-Díaz, Moreno, Gutiérrez & Lozano, 2012)(among others)) to address the BWE in closed-loop supply chains.

The dissertation first defined some hypotheses using conclusions made by previous authors on the same topic. A literature review was used to identify gaps and modelling assumptions used in modelling the BWE in closed-loop systems. The research also identified various methods used in modelling closed-loop systems and detailed why systems dynamics simulation was used for this dissertation. Models were verified and validated and applied to data from the case studies to obtain simulation results. Finally, statistical analyses using MANOVA provided the meaning to the simulation outcomes. With these outcomes, managerial implications and trade-offs on some activities in reverse logistics were provided.

The overall research question was discussed and the research hypotheses tested. This meant that the objectives of the study were met. Knowledge on the BWE in closed-loop systems was enhanced by introducing more factors that need to be considered when introducing a reverse chain to an existing forward chain. Chapter 2 of this dissertation detailed the research articles on BWE in closed-loop systems. The number of articles was less than 30. This shows how the subject is still young. This research added to the topic by exploring a common assumption used by most researchers to model closed-loop systems with remanufacturing. The assumption that remanufacturing and collection capacity is unlimited has been used by all articles that ventured into this topic. This research explored the impact of limiting these capacities on the BWE in the existing forward chain.

The main research question that this study sought to address was, ***"How would the Bullwhip effect in a closed-loop supply chain change if the collection and remanufacturing capacities are limited?"*** Capacity limits became a point of focus of this research on the basis that most organisations involved in reverse logistics operations employ 3PLs because of limitations in resources, infrastructure and technical know-how of some of the reverse supply chain processes. This has not been accounted for by all researchers who ventured into the topic. In order to model closed-loop supply chains more realistically, it was necessary to consider activities in the reverse chain where there might be limitations in capacity and account for the delays and other complications that come about as a result of having these limitations in the reverse chain.

Question 1: How would the BWE in the forward chain be affected by introducing a reverse chain for either reuse or remanufacturing end of use products?

The focus of this research was to measure and investigate the impact on the BWE of various factors that were introduced as a result of introducing a reverse chain to an existing forward chain. The BWE was chosen as a measure of supply chain dynamics because costs associated with this phenomenon have played a pivotal role in some organisations over the years. Costs of setting up and shutting down machines, hiring and firing of workforce, excessive inventory costs and poor customer and supplier relationships (among others) have been associated with the BWE.

The BWE in an already existing forward chain was first measured. How this BWE reacted to the introduction of product returns was then considered. In this case, the research considered factors such as remanufacturing percentage, residence time and reprocessing time. These were the factors already looked into by other researchers on the same topic.

It was discovered that the introduction of product returns to a forward chain stabilised the supply chain by lowering the demand variance at each echelon and this had the impact of lowering the BWE in the supply chain.

Question 2: What is capacity and how is it specified in a closed-loop supply chain?

Before investigating the impact of the capacity limitations, it was necessary to find out how capacity was defined in the context of the reverse supply chain. Chittamvanich (2007) referred to capacity as, "the processing abilities and limitations that stem from the scarcity of various processing resources". The authors further emphasised that capacity can be interpreted as some upper bound on processing quantities.

Heydari, Govindan, and Sadeghi (2018) defined two scenarios of capacity constraints in a closed-loop system;

i. When there is a limited capacity for the remanufacturing of products. In this case too many returned products may cause inefficiency of the reverse logistics system. In this case, excess products that exceeded the remanufacturing capacity were sold as scrap.

ii. When there is sufficient capacity, and insufficient supply of returned products. This causes downtime in the remanufacturing capacity and that downtime causes inefficiency in the reverse operations.

It is these two scenarios that formed the basis of this research to investigate the impact of capacity constraints on the BWE in a closed-loop system.

In defining capacities in the context of closed-loop supply chains, the researcher discovered that most research that modelled capacity expansion policies assumed that the remanufacturing process shared capacity with the forward chain production process. In this case, capacity decisions that affected the remanufacturing process also affected the production process of new products. However, there were several researchers that modelled the closed-loop system with different capacities for remanufacturing and production. This research was one of them.

From this research, following definitions by Cannella (2018), in closed-loop systems, capacity has been defined in terms of upper and lower bounds on the number of products a company can remanufacture per unit time. In closed-loop system, capacity limits have been defined only for the disposition aspect of the reverse logistics process, without considering other aspects such as collection.

Question 3: How do capacity limitations impact the activities of the forward and reverse chain in the supply chain?

Based on the scenarios presented by Heydari, Govindan, and Sadeghi (2018), this dissertation extended some concepts of these scenarios to find out the impact of capacity limits in the closed-loop system. For example, where Heydari, Govindan, and Sadeghi (2018) sold the extra collected products as scrap, this dissertation accumulated extra collected products as remanufacturing backlogs to be processed in the next periods. In a similar way, where the collected products were less than the remanufacturing capacity, instead of underutilising capacity, no remanufacturing took place in that period until the company collected enough products equal to the remanufacturing capacity. By doing all this, the dissertation introduced collection and remanufacturing backlogs in the reverse chain.

This dissertation discovered that, introducing capacity limits to a closed-loop system with remanufacturing increases the BWE as it limits the material flow from the remanufacturing process. However, how the closed-loop system reacts to variations in these capacity limits depends on the demand size and speed of items. For example, the low demand electric vehicle batteries were not affected by the remanufacturing capacity limits at all but the high demand items had their BWE values increase with an increase in the remanufacturing capacities because of order batching and remanufacturing downtime. Both products had their BWE values decrease as the collection capacity limits were increased.

Question 4: How would the Bullwhip effect in a closed-loop supply chain change if the collection and remanufacturing capacities are limited?

Having gained a clear understanding of capacity limitations in a closed-loop system and the scenarios- they present, the systems dynamics models were adjusted to suit each scenario. This research was also unique because it used real case studies to model the closed-loop systems.

From the literature, it was discovered that only one research article considered remanufacturing capacity limits (that of Adenso-Díaz et al. (2012)). This article dismissed remanufacturing capacity limits as being insignificant as far as the BWE in a closed-loop system was concerned. It was interesting to test this theory on real case studies and different supply chain setups as well.

This dissertation noted that the impact of remanufacturing capacity limits depended on the product demand size and speed especially for plants that had to collect enough products before beginning the remanufacturing process. For the low demand items, it was better to collect more products than the remanufacturing capacity and stock them as backlogs, than to collect less products than the remanufacturing capacity and have more periods of remanufacturing downtime. The opposite was true for the high demand items, as their results showed that it is better to have more periods of backlogs than to collect more products than the remanufacturing capacity.

To answer the main research question, introducing capacity limits to a closed-loop system that initially had no capacity limits, increases the BWE at all levels of the supply chain. However, how the closed-loop system responded to variations in these capacity limits depended on the demand size and speed of the products under investigation. It is necessary to consider the demand size in decisions regarding capacity expansion policies in a closed-loop system that has to collect enough products before remanufacturing has to take place.

9.2 Research contribution

The main objective of the dissertation was to build systems dynamics models to measure the BWE in closed-loop systems. The first contribution made by this research is the extension of the evolving topic of the BWE by investigating two concepts mentioned by Wang and Disney (2015). In their invited review, the authors mentioned current trends and extensions for the topic of BWE in supply chains. Among these extensions, the authors mention the BWE in sustainability issues and the BWE in non-linear complex and more realistic systems with capacity limitations. This dissertation combined these two extensions to the topic of BWE by investigating the BWE in supply chains with reverse logistics activities and introducing capacity limits for the reverse logistics processes. Capacity constraints were defined and modelled in the systems dynamics models. Comparisons were also made between scenarios where there were capacity limits and those scenarios where there were no capacity limitations. These comparisons provided useful managerial implications for the case studies involved.

Another contribution made by this research is the identification of a common assumption made by researchers in modelling closed-loop supply chains, that of unlimited capacity in the reverse chain. This is not realistic as there have been researchers who have focused on various capacity expansion policies in reverse supply chain, showing that capacity limitations do exist in the supply chain. This topic was explored by only two articles in literature. One of these is by Adenso-Díaz et al.(2012) and the other by Dominguez et al. (2019). These articles just introduced capacity limits to a closed-loop system and assumed that products are remanufactured as they are collected. This dissertation is different in that it considered organisations that face uncertainties in the quantities of product returns and cannot start remanufacturing until they have collected enough products. This meant that it considered organisations that had periods of remanufacturing downtimes in cases when not enough products were collected. The two authors also did not look into organisations that have access to product returns but had limited collection capacities. In realistic situations, activities of the reverse chain like collection are usually outsourced because of limitations in resources. This dissertation considered the limitations in the collection capacities. Adenso-Díaz et al. (2012) and Dominguez et al. (2019) did not use real case studies in their studies. Their conclusions were based on mathematical simulations. This dissertation looked into two case studies and modelled scenarios based on real-world experiences as described by Heydari, Govindan, and Jafari (2017).

The dissertation not only contributed to literature (there were only two articles for the effects of capacity limits on the BWE in a closed-loop system and 15 articles on the BWE in closed-loop systems), but it also served to verify some findings of previous authors on the BWE in closed-loop systems in addition to its own findings.

The research started off by studying the impact of common factors both in the forward and reverse chain on the BWE. These were investigated under the common assumptions made by previous researchers on the same topic. To further understand how the reverse supply chain affected dynamics in the supply chain, an assumption used by almost all the researchers was relaxed to model a more realistic situation. The assumption that there are no capacity limits was explored as capacity limits were introduced in the form of both collection and remanufacturing capacity. The following conclusions were similar to those of previous research on the BWE in closed-loop system:

1. The BWE in a supply chain does reduce with the introduction of product returns by the end customer irrespective of the product type.
2. Increasing the remanufacturing lead time (in the form of residence time and reprocessing time) increases the BWE in the supply chain at all levels.
3. Increasing the remanufacturing percentage reduces the BWE.

The dissertation also had different conclusions from those of previous authors on the topic and these are summarised below:

1. Adenso-Díaz et al. (2012) concluded that the remanufacturing capacity limit does not have an impact on the BWE. This does not always hold for all product types or where the company has to collect enough products before remanufacturing can start. In this situation, remanufacturing backlogs are introduced to the system and the BWE does respond to remanufacturing capacity limits.

2. In the presence of capacity limits, the conclusion that increasing the remanufacturing percentage reduces the BWE does not always hold especially for companies that have to collect enough before remanufacturing begins. The impact of remanufacturing percentage in the presence of capacity limits depends on the demand type and speed.

There were also additional findings made by this dissertation and these are listed below:

1. For low demand and slow moving items, it would be beneficial to introduce both collection and remanufacturing capacity limits than just one of them. This had a strong impact on reducing the BWE in the closed-loop system.
2. Low demand and slow moving items (electric vehicle batteries) reacted differently to collection and remanufacturing capacity limits than high demand and high speed items (kitchen appliances).
3. The presence of external returns that are not regulated by the organisation not only impacts the BWE but also how the other factors affect the BWE, and should therefore be taken into consideration when modelling closed-loop systems.

9.3 Future research directions

Although this research did provide some insights on the presence of capacity limitations in closed-loop systems, there is still a need for more exploration into this topic. Firstly, although the research was empirical, it was based on average and fixed values provided by the organisations. It would be better to find a case study from an organisation that is willing to provide historical data especially on demand patters. This research assumed the exponential smoothing method of forecasting, but there is a chance that some organisations may have other methods of forecasting and historical data can assist in identifying such trends.

The assumption of stationary demand to make the mathematical formulation easier should also be extended by considering stochastic models of demand. Again, this can only be done if one can find a case study that is willing to provide historical data. Most organisations approached felt threatened by the technical information required to mathematically model the closed-loop systems.

The research assumed that the remanufacturing capacity was not in any way related to the production capacity and inventory management principles in the reverse chain did not affect those of the forward chain. It would be interesting to explore situations in which the production and remanufacturing processes shared capacity and where inventory management policies for both the reverse and the forward chain were interconnected. The impact on the supply chain dynamics of such a connection would be an interesting find.

Finally, the research assumed that the organisation had no option for expanding capacity in the presence of capacity limits. In the real world, most organisations outsource some activities of the reverse chain such as collection to waste pickers and 3PLs. It is a desire of the researcher to investigate the impact of both capacity limitations and outsourcing policies on the BWE in the closed-loop system.

References

Adelson, R.. M. 1966. The Dynamic Behaviour of Linear Forecasting and Scheduling Rules. *Operations Research*. 17(4):447–462.

Adenso-Díaz, B., Moreno, P., Gutiérrez, E. & Lozano, S. 2012. An analysis of the main factors affecting bullwhip in reverse supply chains. *International Journal of Production Economics*. 135(2):917–928.

Akkermans, H. & Vos, B. 2003. Amplification is service supply chains: An exploratory case study from the Telecom industry*. *Production and Operations Management*. 12(2):204–224.

Akkermans, H. & Voss, C. 2013. The service bullwhip effect. *International Journal of Operations & Production Management*. 33(6):765–788.

Aksoy, H.K. & Gupta, S.M. 2001. Capacity and buffer trade-offs in a remanufacturing system. In *Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing II*. 167–174.

Alony, I. & Aneiros, A.M. 2007. The Bullwhip effect in complex supply chains. In *International Symposium on Communications and Information Technologies ISCIT*. 1355–1360.

Aras, N., Boyaci, T. & Verter, V. 2004. The effect of categorizing returned products in remanufacturing. *IIE Transactions (Institute of Industrial Engineers)*. 36(4):319–331.

Asif, F.M.A., Bianchi, C., Rashid, A. & Nicolescu, C.M. 2012. Performance analysis of the closed loop supply chain. *Journal of Remanufacturing*. 2(4):1–21.

Atasu, A., Guide, V.D.R. & Van Wassenhove, L.N. 2008. Product Reuse Economics in Closed-Loop Supply Chain Research. *Production and Operations Management*. 17(5):483–496.

Barlas, Y. 1996. Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*. 12(3):183–210.

Beamon, B.M. & Chen, V.C.P. 2001. Performance Analysis of Conjoined Supply Chains. *International Journal of Production Research*. 39(14):3195–3218.

Behdani, B. 2012. Evaluation of paradigms for modelling supply chains as complex socio-technical systems. In C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, & A.M. Uhrmacher (eds.) *Proceedings of the 2012 Winter Simulation Conference*.

Beltran, J.L. & Krass, D. 2002. Dynamic lot sizing with returning items and disposals. *IIE Transactions (Institute of Industrial Engineers)*. 34(5):437–448.

Bertrand, J. 1986. Balancing production level variations and inventory variations in complex production systems. *International Journal of Production Research*. 24(5):1059–1074.

Bertrand, J.W.M. 1980. Analysis of a production-inventory control system for a diffusion department. *International Journal of Systems Science*. 11(5):589–606.

Blackburn, J.D., Guide Jr, V.D.R., Souza, G.C. & Van Wassenhove, L.N. 2004. Reverse

Supply Chains for Commercial Returns. *California Review Management*. 46(2):6–23.

Le Blanc, H.M. 2006. Closing loops in supply chain management: designing reverse supply chains for end-of-life vehicles.Unpublished doctoral dissertation. University of Tilburg.

Bloemhof-Ruwaard, J.M., Van Wassenhove, L.N., Gabel, H.L. & Weaver, P.M. 1996. An environmental life cycle optimization model for the European pulp and paper industry. *Omega*. 24(6):615–629.

Bokade, S. 2014. Flexibility and effectiveness in reverse logistics of product returns in the form of parts and sub-assemblies. *International Journal of Development Research*. 4(3):491–495.

Borshchev, A. & Filippov, A. 2004. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. In *The 22nd Conference of the Systems Dynamics Society*.

de Brito, M.P. & Dekker, R. 2002. Reverse Logistics - a framework. *Econometric Institute Report EI 2002-38*. (November):1–19.

Brown, R. 1963. *Smoothing, forecasting and prediction of discrete time series*. New Jersey: Prentice-Hall Inc.

Cachon, G.P., Randall, T. & Schmidt, G.M. 2007. In Search of the Bullwhip Effect. *Manufacturing & Service Operations Management*. 9(4):457–479.

Cannella, S., Ciancimino, E. & Marquez, A.C. 2008. Capacity constrained supply chains : A simulation study. *International Journal of Simulation and Process Modelling*. 4(2).

Cannella, S., Barbosa-Póvoa, A.P., Framinan, J.M. & Relvas, S. 2013. Metrics for bullwhip effect analysis. *Journal of the Operational Research Society*. 64(1):1–16.

Cannella, S., Bruccoleri, M. & Framinan, J.M. 2016. Closed-loop supply chains : What reverse logistics factors in fl uence performance ? *International Journal of Production Economics*. 175:35–49.

Cannella, S., Dominguez, R., Ponte, B. & Framinan, J.M. 2018. Capacity restrictions and supply chain performance: Modelling and analysing load-dependant lead times. *International Journal of Production Economics*. 204:264–277.

Cao, B.-B., Xiao, Z.-D. & Sun, J.-N. 2017. A study of the bullwhip effect in supply- and demand-driven supply chain. *Journal of Industrial and Production Engineering*. 34(2):124–134.

Cavazzuti, M. 2013. Design of Experiments. In Springer *Optimization Methods: From Theory to Design Scientific and Technological Aspects in Mechanics*. 1–262.

Chang, Y. & Makatsoris, H. 2002. Supply chain modeling using simulation. *International Journal of Simulation*. 2(1):24–30.

Chatfield, D.C. 2013. Underestimating the bullwhip effect: A simulation study of the decomposability assumption. *International Journal of Production Research*. 51(1):230–244.

Chatfield, D.C., Kim, J.G., Harrison, T.P. & Hayya, J.C. 2004. The Bullwhip Effect — Impact of Stochastic Lead Time , Information Quality , and Information Sharing : A Simulation Study. *Production & Operations Management*. 13(4):340–353.

Chaturvedi, D.K. 2010. *Modelling and Simulation of Systems using MATLAB and SIMULINK*. CRC Press: Taylor and Francis Group.

Chen, L. & Lee, H.L. 2012. Bullwhip Effect Measurement and Its Implications Bullwhip Effect Measurement and Its Implications. *Operations Research*. 60(4):771–784.

Chen, F., Drezner, Z., Ryan, J.K. & Simchi-levi, D. 2000. Quantifying the Bullwhip Effect in a Simple Supply Chain : The Impact of Forecasting , Lead Times , and Information. *Management Science*. 46(3):436–443.

Chittamvanich, S. 2007. Adjusting remanufacturing capacity using sales and return information. IOWA STATE UNIVERSITY.

Chopra, S. & Meindl, P. 2007. *SUPPLY CHAIN MANAGEMENT: Strategy, Planning and Operation*. 3rd ed. M. Pfaltzraff (ed.). Pearson Prentice Hall.

Cimbala, J.M. 2014. *Taguchi Orthogonal Arrays*.

Cobb, B.R. 2016. Inventory control for returnable transport items in a closed-loop supply chain. *Transportation Research Part E*. 86:53–68.

Coppini, M., Rossignoli, C., Rossi, T. & Strozzi, F. 2010. Bullwhip effect and inventory oscillations analysis using the beer game model. *International Journal of Production Research*. 48(13):3943–3956.

Corum, A., Vayvay, O. & Bayraktar, E. 2014. The impact of remanufacturing on total inventory cost and order variance. *Journal of Cleaner Production*. 85:442–452.

Costantino, F., Di Gravio, G., Shaban, A. & Tronci, M. 2015. SPC forecasting system to mitigate the bullwhip effect and inventory variance in supply chains. *Expert Systems with Applications*. 42(3):1773–1787.

Costas, J., Ponte, B., de la Fuente, D., Pino, R. & Puche, J. 2015. Applying Goldratt's Theory of Constraints to reduce the Bullwhip Effect through agent-based modeling. *Expert Systems with Applications*. 42(4):2049–2060.

Dai, H., Li, J., Yan, N. & Zhou, W. 2016. Bullwhip effect and supply chain costs with low- and high-quality information on inventory shrinkage. *European Journal of Operational Research*. 250(2):457–469.

Daniel, V., Guide Jr, R. & Jayaraman, V. 2000. Product acquisition management : current industry practice and a proposed framework. *International Journal of Production Research*. 38(16):3779–3800.

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

Dejonckheere, J., Disney, S.M., Lambrecht, M.R. & Towill, D.R. 2003. Measuring and avoiding the bullwhip effect: A control theoretic approach. *European Journal of Operational Research*. 147(3):567–590.

Dejonckheere, J., Disney, S.M., Lambrecht, M.R. & Towill, D.R. 2004. The impact of information enrichment on the Bullwhip effect in supply chains: A control engineering perspective. *European Journal of Operational Research*. 153(3):727–750.

Deziel, D.P. & Eilon, S. 1967. A linear production -inventory control rule. *The Production Engineer*. 43:93–104.

Ding, X. & Gan, X. 2009. System Dynamics Model to Analysis Oscillation and Amplification in the Closed-Loop Supply Chain. In *International Conference on Management of e-Commerce and e-Government*. 343–346.

Disney, S.M. & Lambrecht, M.R. 2008. On replenishment rules , forecasting and the bullwhip effect in supply chains. *Foundations and Trends in Technology, Information and Operations Management*. 2(1):1–80.

Disney, S.M. & Towill, D.R. 2002. A discrete transfer function model to determine the dynamic stability of a vendor managed inventory supply chain. *International Journal of Production Research*. 40(1):179–204.

Disney, S.M. & Towill, D.R. 2003. On the bullwhip and inventory variance produced by an ordering policy. *Omega*. 31(3):157–167.

Disney, S.M., Towill, D.R. & Van De Velde, W. 2004. Variance amplification and the golden ratio in production and inventory control. *International Journal of Production Economics*. 90(3):295–309.

Domgala, T. & Woliniak, R. 2013. Reverse Supply Chain. *Management Systems in Production Engineering*. 4(12):3–7.

Dominguez, R., Cannella, S. & Framinan, J.M. 2014. The impact of the supply chain structure on bullwhip effect. *Applied Mathematical Modelling*. 39(23–24):7309–7325.

Dominguez, R., Ponte, B., Cannella, S. & Framinan, J.M. 2019. On the dynamics of closed-loop supply chains with capacity constraints. *Computers & Industrial Engineering*. 128(December 2018):91–103.

Duan, Y., Yao, Y. & Huo, J. 2015. Bullwhip effect under substitute products. *Journal of Operations Management*. 36:75–89.

Editor, M.B. 2014. *The Power of Multivariate ANOVA (MANOVA) available https://blog.minitab.com/blog/adventures-in-statistics-2/the-power-of-multivariate-anova-manova [13 March 2019]*.

El-Beheiry, M., Wong, C.Y. & El-Kharbotly, A. 2004. Empirical quantification of bullwhip effect (With application to a toy supply chain). In *Thirteenth International Working Seminar on Production Economics*.

Ellram, L.M. 1996. The Use of the Case Study Study Method in Logistics Research. *Journal of Business Logistics*. 17(2, Business Premium Collection):93–138.

Ellram, L.M. & Cooper, M.C. 1990. Supply Chain Management, Partnership, and the Shipper - Third Party Relationship. *The International Journal of Logistics Management*. 1(2):1–10.

Evans, G.. & Naim, M.M. 1994. The dynamics of Capacity constrained Supply chains. In *International Systems Dynamics Conference*. 28–33.

Feng, L., Zhang, J. & Tang, W. 2013. Optimal control of production and remanufacturing for a recovery system with perishable items. *International Journal of Production Research*. 51(13):3977–3994.

Ferguson, M.E. & Toktay, L.B. 2006. The Effect of Competition on Recovery Strategies. *Production and Operations Management*. 15(3):351–368.

Ferrer, G. & Whybark, D.C. 2001. Material Planning for a Remanufacturing Facility. *Production and Operations Management*. 10(2):112–124.

Fleischmann, M. 2000. Quantitative Models for Reverse Logistics. Published doctoral dissertation.ERIM Ph.D series Research in Management nr. 2. Erasmus University Roterdam.

Fleischmann, M. 2001. Reverse Logistics Network Structures and Design. *Business perspectives on closed-loop supply chains*. 1–21.

Flynn, B.B., Sakakibara, S., Schroeder, R.G., Bates, K.A. & Flynn, E.J. 1990. Empirical research methods in operations management. *Journal of Operations Management*. 9(2):250–284.

Forrester, J.W. 1961. *Industrial Dynamics*. Cambridge: MIT Press.

Forrester, J.W. & Senge, P.M. 1980. Tests for building confidence in Systems Dynamics Models. In 14th ed. North Holland Publishing Company *TIMS Studies in the Management Sciences*. 209–228.

Fransoo, J.C. & Wouters, M.J.. F. 2000. Measuring the bullwhip effect in the supply chain. *Supply Chain Management*. 5(2):78–89.

Fu, D., Ionescu, C.M., Aghezzaf, E. & De Keyser, R. 2014. Decentralized and centralized model predictive control to reduce the bullwhip effect in supply chain management. *Computers & Industrial Engineering*. 73:21–31.

Fu, D., Ionescu, C., Aghezzaf, E.H. & De Keyser, R. 2015. Quantifying and mitigating the bullwhip effect in a benchmark supply chain system by an extended prediction self-adaptive control ordering policy. *Computers and Industrial Engineering*. 81:46–57.

Galbreth, M.R. & Blackburn, J.D. 2006. Optimal acquisition and sorting policies for remanufacturing. *Production and Operations Mangement*. 15(3):384–392.

Geary, S., Disney, S.M. & Towill, D.R. 2006. On Bullwhip in Supply Chains ~ Historical Review , Present Practice and Expected Future Impact. *International Journal of Production Economics*. 101(1).

George, J. & Pillai, V.M. 2016. Transfer Function Models of Inventory Policies and Bullwhip

Quantification in Supply Chain. *Procedia Technology*. 25:1064–1071.

Georgiadis, P. & Athanasiou, E. 2013. Flexible long-term capacity planning in closed-loop supply chains with remanufacturing. *European Journal of Operational Research*. 225(1):44–58.

Geyer, R. & Jackson, T. 2004. Supply Loops and Their Constraints: The Industrial Ecology of Recycling and Reuse. *California Management Review*. 46(2 REPRINT SERIES).

Golany, B., Yang, J. & Yu, G. 2001. Economic lot-sizing with remanufacturing options. *IIE Transactions (Institute of Industrial Engineers)*. 33(11):995–1003.

Gong, X. & Chao, X. 2013. Technical Note—Optimal Control Policy for Capacitated Inventory Systems with Remanufacturing. *Operations Research*. 61(3):603–611.

Goodarzi, M., Makvandi, P., Saen, R.F. & Sagheb, M.D. 2017. What are causes of cash flow bullwhip effect in centralized and decentralized supply chains? *Applied Mathematical Modelling*. 44:640–654.

Gorman, M.F. & Kanet, J.J. 2011. Toward a Better Understanding of the Bullwhip Effect. *Production and Inventory Management Journal*. 47(1):33–43.

Graves, S.C. 1997. *A Single-Item Inventory Model for a Nonstationary Demand Process. Working paper number 3944.Massachusetts Institute of Technology.*

Guide, V.D.R. & Jiayi, L. 2010. The potential for cannibalization of new products sales by remanufactured products. *Decision Sciences*. 41(3):547–572.

Guide Jr, V.D.R. 1996. Scheduling using drum-buffer-rope in a remanufacturing environment. *International Journal of Production Research*. 34(4).

Guide Jr, V.D.R. & Van Wassenhove, L.N. 2009. The Evolution of Closed Loop Supply Chain Research. *Operations Research*. 57(1):10–18.

Gupta, A.K., O.P, S. & R.K, G. 2012. Evolution and development of the Bullwhip effect and its contribution towards the supply chain management: A literature review. *International journal of Management and Information Technology*. 1(3).

Haines, R., Hough, J. & Haines, D. 2017. A metacognitive perspective on decision making in supply chains: Revisiting the behavioral causes of the bullwhip effect. *International Journal of Production Economics*. 184(February 2016):7–20.

He, S., Yuan, X. & Zhang, X. 2016. The Government's environment policy index impact on recycler behavior in electronic products closed-loop supply chain. *Discrete Dynamics in Nature and Society*. 2016:1–8.

Heydari, J., Govindan, K. & Jafari, A. 2017. Reverse and closed loop supply chain coordination by considering government role. *Transportation Research Part D: Transport and Environment*. 52:379–398.

Heydari, J., Govindan, K. & Sadeghi, R. 2018. Reverse supply chain coordination under stochastic remanufacturing capacity. *International Journal of Production Economics*. 202(March):1–11.

Hillston, J. 2003. Model validation and verification. In *www.inf.ed.ac.uk/teaching/courses/ms/notes/note 14*.

Hintze, J.L. 2007. D-Optimal designs. In NCSS *NCSS User's Guide II Descriptive Statistics, Means, Quality Control, and Design of Experiments*. 267-1–23.

Holweg, M. & Disney, S.M. 2005. The evolving frontiers of the bullwhip effect. In Budapest *EUROMA Annual Conference*.

Hosoda, T. & Disney, S.M. 2004. The Role of an Ordering Policy As an Inventory and Cost Controller. In *Proceedings of the Logistics Research Network Annual Conference*. 1–8.

Hosoda, T., Altekin, F.T. & Sahin, G. 2015. The impact of information sharing, random yield correlation and lead times in closed loop suply chains. *European Journal of Operational Research*. 246:827–836.

Hussain, M. & Drake, P.R. 2011. Analysis of the bullwhip effect with order batching in multi-echelon supply chains. *International Journal of Physical Distribution & Logistics Management*. 41(8):797–814.

Inderfurth, K. 1997. Simple optimal replenishment and disposal policies for a product recovery system with leadtimes. *OR Spectrum*. 19(2):111–122.

Jia, S., Wang, L. & Luo, C. 2011. The Research on Stability of Supply Chain under Variable Delay Based on System Dynamics. In S. Renko (ed.). InTech *Supply Chain Management: New Perspectives*.

Jin, Y. "Henry", Williams, B.D., Waller, M.A. & Hofer, A.R. 2015. Masking the bullwhip effect in retail: the influence of data aggregation. *International Journal of Physical Distribution & Logistics Management*. 45(8):814–830.

Jonathan Thatcher. 2016. *Thinking Supply Chain:Will the next 15 years be a logistics golden age?* [Online], Available: http://www.apics.org/sites/apics-blog/think-supply-chain-landing-page/thinking-supply-chain/2016/07/21/will-the-next-15-years-be-a-logistics-golden-age [2018, January 02].

Kelepouris, T., Miliotis, P. & Pramatari, K. 2008. The impact of replenishment parameters and information sharing on the bullwhip effect: A computational study. *Computers and Operations Research*. 35(11):3657–3670.

Ketzenberg, M.E., Guide, D.J. & Souza, G.C. 2003. Mixed Assembly and Disassembly Operations for Remanufacturing. *Production and Operations Management*. 12(3):320–335.

Kirk, R.E. 2013. Experimental design. In John Wiley & Sons Ltd *Handbook of psychology, Vol. 2: Research methods in psychology*. 3–33.

Krikke, H., Le Blanc, L. & Van de Velde, S. 2004. Product Modularity and the Design of Closed-Loop Supply Chains. *California Management Review*. 46(2 REPRINT SERIES).

van der Laan, E., Salomon, M., Dekker, R. & Van Wassenhove, L. 1999. Inventory Control in Hybrid Systems with Remanufacturing. *Management Science*. 45(5):733–747.

Van der Laan, E., Salomon, M., Dekker, R. & Wassenhove, L. Van. 1999. Inventory Control in

Hybrid Systems with Remanufacturing. *Management Science*. 45(5):733–747.

Lambert, D.M. & Cooper, M.C. 2000. Issues in Supply Chain Management. *Industrial Marketing Management*. 29:65–83.

Larsen, E.R., Morecroft, J.D.W. & Thomsen, J.S. 1999. Complex behaviour in a production-distribution model. *European Journal of Operational Research*. 119(1):61–74.

Lee, H.L., Padmanabhan, V. & Whang, S. 1997. Information Distortion in a Supply Chain: The Bullwhip Effect. *Management Science*. 43(4):546–558.

Li, Q., Disney, S.M. & Gaalman, G. 2014. Avoiding the bullwhip effect using Damped Trend forecasting and the Order-Up-To replenishment policy. *International Journal of Production Economics*. 149:3–16.

Lieckens, K. 2009. Reverse Logistics Network Design: The Impact of Lead Times and Stochasticity.Unpublished thesis. University of Antwerp, Belgium.

Lin, P.H., Wong, D.S.H., Jang, S.S., Shieh, S.S. & Chu, J.Z. 2004. Controller design and reduction of bullwhip for a model supply chain system using z -transform analysis. *Journal of Process Control*. 14(5):487–499.

Lin, W., Jiang, Z. & Wang, L. 2014. Modelling and analysis of the bullwhip effect with customers ' baulking behaviours and production capacity constraint. *International Journal of Production Research*. 52(16):4835–4852.

Lin, W.-J., Jiang, Z., Liu, R. & Wang, L. 2014. The bullwhip effect in hybrid supply chain. *International Journal of Production Research*. 52(7):2062–2084.

Ma, J. & Ma, X. 2017. Measure of the bullwhip effect considering the market competition between two retailers. *International Journal of Production Research*. 55(2):313–326.

Ma, L. & Chai, Y. 2014. Dynamics Modelling of Bullwhip Effect in Remanufacturing Closed-Loop Supply Chain based on Third-party Recycler. *Information Technology Journal*. 13(13):2137–2144.

Ma, L., Chai, Y., Zhang, Y. & Zheng, L. 2014. Modelling and Analysis of the Bullwhip Effect in Remanufacturing. *Applied Mechanics and Materials*. 541–542:1556–1561.

Ma, Y., Wang, N., He, Z., Lu, J. & Liang, H. 2015. Analysis of the bullwhip effect in two parallel supply chains with interacting price-sensitive demands. *European Journal of Operational Research*. 243(3):815–825.

Mackelprang, A.W. & Malhotra, M.K. 2015. The impact of bullwhip on supply chains: Performance pathways, control mechanisms, and managerial levers. *Journal of Operations Management*. 36:15–32.

Magee, J. 1958. *Production Planning and Inventory Control*. London: Irwin McGraw-Hill.

Mason-Jones, R., Naim, M.M. & Towill, D.R. 1997. The Impact of Pipeline Control on Supply Chain Dynamics. *International Journal of Logistics Management*. 8(2):47–62.

Matsuyama, K. 1997. Maintaining optimal inventory level by feedbacks. *International Journal of Production Economics*. 53(1):57–69.

McHaney, R. 2009. *Understanding Computer Simulation*. first ed. bookboon.com.

Mentzer, J.T., Keebler, J.S., Nix, N.W., Smith, C.D. & Zacharia, Z.G. 2001. Defining Supply Chain Management. *Journal of Business Logistics*. 22(2).

Meredith, J. 1998. Building operations management theory through case and field research. *Journal of Operations Management*. 16:441–454.

Meredith, J.R., Raturi, A., Amoako-Gyampah, K. & Kaplan, B. 1989. Alternative Research Paradigms in Operations. *Journal of Operations Management*. 8(4):297–326.

Miles, T. 2013. *Trith, Lies, and Statistical Modelling in Supply Chain-Part 1 available on https://blog.kinaxis.com/2013/02/truth-lies-and-statistical-modeling-in-supply-chain/ [2019, February 29]*.

Minitab Blog, E. 2019. *Overview for correlation available on https://support.minitab.com/en-us/minitab-express/1/help-and-how-to/modeling-statistics/regression/how-to/correlation/overview/ [2019 May 29]*.

Murray, M. 2018. *Supply Chain Management : Measuring Capacity in Manufacturing available on https://www.thebalancesmb.com/measuring-capacity-in-manufacturing-2221213 [2018 October 22]*.

Nagaraja, C.H., Thavaneswaran, A. & Appadoo, S.S. 2015. Measuring the bullwhip effect for supply chains with seasonal demand components. *European Journal of Operational Research*. 242(2):445–454.

Nepal, B., Murat, A., Chinnam, R.B. & Babu Chinnam, R. 2012. The bullwhip effect in capacitated supply chains with consideration for product life-cycle aspects. *International Journal of Production Economics*. 136(2):318–331.

Oral, M. & Kettani, O. 1993. The facets of the modelling and validation process in operations research. *European Journal of Operational Research*. 66(2).

Owen, C., Albores, P. & Greasley, D. 2010. Similation in the supply chain context : Matching the simulation tool to the problem. In *Proceedings of the Operational Research Society Simulation Workshop (SW10)*. 229–242.

Paik, S.-K. & Bagchi, P.K. 2007. Understanding the causes of the bullwhip effect in a supply chain. *International Journal of Retail & Distribution Management*. 35(4):308–324.

Poles, R. 2013. System Dynamics modelling of a production and inventory system for remanufacturing to evaluate system improvement strategies. *International Journal of Production Economics*. 144(1):189–199.

Poles, R. & Cheong, F. 2011. An Investigation on Capacity Planning and Lead Times for Remanufacturing Systems Using System Dynamics BT -. In *44th Hawaii International Conference on System Sciences (HICSS 2011)*. 1–10.

Ponte, B., Wang, X., de la Fuente, D. & Disney, S.M. 2017. Exploring nonlinear supply chains : the dynamics of capacity constraints. *International Journal of Production Research*. 55(14):4053–4067.

Prahinski, C. & Kocabasoglu, C. 2006. Empirical research opportunities in reverse supply chains. *International Journal of Management Science*. 34:519–532.

Raghunathan, S. 2001. Information Sharing in a Supply Chain: A Note on its Value when Demand Is Nonstationary. *Management Science*. 47(4):605–610.

Ramaekers, K. & Janssens, G.K. 2008. On the choice of a demand distribution for inventory management models. *European J. of Industrial Engineering*. 2(4):1–15.

Riddalls, C.E., Bennett, S. & Tipi, N.S. 2000. Modelling the dynamics of supply chains. *International Journal of Systems Science*. 31(8):969–976.

Robinson, S. 2004. *Simulation: The practice of Model Development and use*. John Wiley & Sons, Ltd.

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

de Ron, A. & Penev, K. 1995. Disassembly and recycling of electronic consumer products: An overview. *Technovation*. 15(5):363–374.

Rose, S., Spinks, N. & Canhoto, A.I. 2015. Case study research design. In Routledge *Management Research: Applying the Principles*. 420.

Sadeghi, A. 2015. Providing a measure for bullwhip effect in a two-product supply chain with exponential smoothing forecasts. *International Journal of Production Economics*. 169:44–54.

Savrasov, M. 2008. Overview of flow systems investigation and analysis methods. In *The 8th International Conference "Reliability and Statistics in Transportation and Communication"*. 273–280.

Schneeweiss, C. 1975. Dynamic certainty equivalents in production smoothing theory. *International Journal of Systems Science*. (4):353–365.

Schneider-Maul, R. 2017. *The future of Supply Chain Management-A trend analysis available on https://www.capgemini.com/2018/the future of supply chain management / [2018 February 1]*.

Silver, E.A. & Peterson, R. 1985. *Decision Systems for Inventory Management and Production Planning*. 2nd ed. John Wiley & Sons, Ltd.

Simchi-levi, D., Kamnsky, P. & Simchi-Levi, E. 2008. *Designing and Mananging the Supply Chain- Concepts, Strategies and Case Studies*. 3rd editio ed. Mcgraw Hill- Irwin.

Simon, H.A. 1952. On the Application of Servomechanism Theory in the Study of Production. *Econometrica : Journal of the Econometric Society*. 20(2):247–268.

Sirikasemuk, K. & Luong, H.T. 2017. Measure of bullwhip effect in supply chains with first-order bivariate vector autoregression time-series demand model. *Computers and Operation Research*. 78:59–79.

de Souza, R., Zice, S. & Chaoyang, L. 2000. Supply chain dynamics and optimization. *Integrated Manufacturing Systems*. 11(5):348–364.

Spiegler, V.L.M. & Naim, M.M. 2014. The impact of freight transport capacity limitations on supply chain dynamics. *International Journal of Logistics Research and Applications*. 17(1):64–88.

Steckel, J.H., Gupta, S. & Banerji, A. 2004. Supply Chain Decision Making: Will Shorter Cycle Times and Shared Point-of-Sale Information Necessarily Help? *Management Science*. 50(4):458–464.

Sterman, J.D. 1989. Modeling Managerial Behavior : Misperceptions of Feedback in a Dynamic Decision Making Experiment. *Management Science*. 35(3):321–339.

Sterman, J.D. 2000. *BUSINESS DYNAMICS: Systems Thinking and Modeling for a Complex World*. S. Insenberg (ed.). Mcgraw Hill- Irwin.

Stoecker, R. 1991. Evaluating and Rethinking the Case Study. *The Sociological Review*. 39:88–112.

Sucky, E. 2009. The bullwhip effect in supply chains-An overestimated problem? *International Journal of Production Economics*. 118(1):311–322.

Sy, C. 2017. A policy development model for reducing bullwhips in hybrid production-distribution systems. *International Journal of Production Economics*. 190:67–79.

Tako, A.A. & Robinson, S. 2012. The application of discrete event simulation and system dynamics in the logistics and supply chain context. *Decision Support Systems*. 52(4):802–815.

Tang, O. & 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(19):4135–4152.

Tang, O. & Teunter, R. 2006. Economic Lot Scheduling Problem with Returns. *Production & Operations Management*. 15(4):488.

Tarokh, M.J. & Golkar, M. 2006. Supply Chain Simulation Methods. *IEEE*.

Thierry, M., Salomon, M., Van Nunen, J. & Van Wassenhove, L. 1995. Strategic Issues in Product Recovery Management. *California Management Review*. 37:114–134.

Toffel, M.W. 2003. The Growing Strategic Importance of End-of-Life Product Management. *California Management Review*. 45(3 REPRINT SERIES):101–130.

Towill, D.R. 1982. Dynamic analysis of an inventory and order based production control system. *International Journal of Production Research*. 20:671–687.

Trapero, J.R. & Pedregal, D.J. 2016. A novel time-varying bullwhip effect metric: An application to promotional sales. *International Journal of Production Economics*. 182(November 2015):465–471.

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

Vasil, T.J. 2011. “Forward Thinking in Reverse”-Design, Implementation, and continous

Monitoring of a Closed-Loop Supply Chain using Optimization, Simulation, and Dashboard Systems to Maximize Net Recovery. Published thesis. Sloan School of Management.; Massachusetts Institute of Technology.

Vassian, H.J. 1955. Application of Discrete Variable Servo Theory to Inventory Control. *Journal of the Operations Research Society of America*. 3(3):272–282.

Vlachos, D., Georgiadis, P. & Iakovou, E. 2007. A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains. 34:367–394.

Wan, Z. & Li, C.-B.C. 2012. Bullwhip effect in closed-loop supply chain based on system dynamics. *Computer Integrated Manufacturing Systems, CIMS*. 18(5):1093–1098.

Wang, X. & Disney, S.M. 2015. The bullwhip effect: Progress, trends and directions. *European Journal of Operational Research*. 250:691–701.

Wang, X. & Disney, S.M. 2017. Mitigating variance amplification under stochastic lead-time: The proportional control approach. *European Journal of Operational Research*. 256(1):151–162.

Wang, Q., Li, J., Yan, H. & Zhu, S.X. 2016. Optimal remanufacturing strategies in name-your-own-price auctions with limited capacity. *International Journal of Production Economics*. 181:113–129.

Wang, Z., Wang, X. & Ouyang, Y. 2015. Bounded growth of the bullwhip effect under a class of nonlinear ordering policies. *European Journal of Operational Research*. 247(1):72–82.

Wei, S., Tang, O. & Sundin, E. 2015. Core (product) Acquisition Management for remanufacturing: a review. *Journal of Remanufacturing*. 5(1):4.

Wells, P., Seitz, M. & Seitz, M. 2005. Business models and closed-loop supply chains : a typology. *Supply Chain Manaement: An International Journal*. 10(4).

Yin, R.K. 1994. Designing Case Studies. In second edi ed. Vol. Applied So. SAGE Publications Ltd *Case Study Reserach - Design and Methods*. 1–53.

Yuan, X. & Zhang, X. 2015. Recycler Reaction for the Government Behavior in Closed-Loop Supply Chain Distribution Network : Based on the System Dynamics. *Discrete Dynamics in Nature and Society*. 2015:11.

Zanoni, S., Ferretti, I. & Tang, O. 2006. Cost performance and bullwhip effect in a hybrid manufacturing and remanufacturing system with different control policies. *International Journal of Production Research*. 44(18–19):3847–3862.

Zhang, X. & Yuan, X. 2016. The System Dynamics Model in Electronic Products Closed-Loop Supply Chain Distribution Network with Three-Way Recovery and the Old-for-New Policy. *Discrete Dynamics in Nature and Society*. 2016:10.

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

Zhou, L., Disney, S.M., Lalwani, C.S. & Wu, H. 2004. Reverse logistics: A study of bullwhip in continuous time. In Vol. 4 *Proceedings of the 5th World Congress on Intelligent Control* *and Automation (WCICA)*. 3539–3542.

Zhou, L., Naim, M.M. & Disney, S.M. 2017. The impact of product returns and remanufacturing uncertainties on the dynamic performance of a multi-echelon closed-loop supply chain. *International Journal of Production Economics*. 183:487–502.

Zotteri, G. 2013. An empirical investigation on causes and effects of the Bullwhip-effect: Evidence from the personal care sector. *International Journal of Production Economics*. 143(2):489–498.

Appendices

Appendix A: Examples of Open and Closed-Loop Supply Chains

This appendix lists common companies operating reverse logistics operations classified into open loop and closed loop systems.

Company	Products	Country	Motivation	Strategy	Activities	Brief Description
AMD	Microprocessors	USA	Regulation	Internal Reuse	Reuse	Donation program for reclaimed processors for schools and charities.
Apple	Computers	USA	Economic	Open Group Recycling	Recycling	Taken back equipment goes to 3P recycler who specialises in e-waste.
Armstrong	Ceiling tiles	USA	Economic	Internal Closed Loop Recycling	Recycling	Collects old tiles from large replacement projects, grinds them, and mixes them with virgin materials to make new tiles.
Bosch	Power tools, auto parts, rechargeable batteries	Germany	Economic	Internal Value Capture	Remanufacturing Recycling	Remanufactures Bosch power tools for resale, remanufactures auto parts for various OEMs, recycles rechargeable batteries
Canon	Photography printing	Japan	Economic	Internal value capture	Reuse Recycling	Cannibalize Cannon printer cartridges, plastic recycled in house, metals recycled by an outside company
Brother	Office Automation Equipment	Japan	Economic	Internal Reuse	Reuse	Collects used printer cartridges which it refills in house for resale.

Chaco Sandals	Footwear	USA	Economic	Internal Reuse	Repair Reuse	Sandals are designed to be repaired and old Chacos are collected to be resold in third world countries
Fuji	Cameras	Japan	Responsible	Internal Value Capture	Cannibalization Recycling	Dis assembles its one time use cameras. Lenses and electronic flash units are reused. Bodies and other parts recycled.
IKEA	furniture	Sweden	Responsible	Open group recycling	recycle	Recycling program for high efficiency light bulbs
Motorola	telecoms	USA	Economic	Closed group recycling Internal value capture	Recycling remanufacturing	In Thailand, purely recycles phones and remanufactures in the US.
NIKE	footwear	USA	Economic	Open group recycling	recycling	Collects old sneakers and recycles them into running paths and tracks
Nokia	telecoms	Finland	Economic	External value capture Closed group recycling	Remanufacturing recycling	Remanufactures phones and uses 3P to recycle mobile phone batteries

Appendix B: Thesis case study protocol

A cause study protocol was used for collecting data from the two companies and the structure of this case study protocol is shown in this appendix.

Study Title: A systems dynamics model to measure the impact of third party reverse logistics providers on closed-loop supply chain performance

Chief Investigator: LOCADIA LINDA TOMBIDO

Investigators: Dr. Louis Louw, Dr Joubert Van Eeden

Sponsor: Stellenbosch University

Chief Investigator Signature:

Confidentiality Statement

This document contains confidential information that must not be disclosed to anyone other than the Sponsor, the Investigator Team, host organisation, and members of the Research Ethics Committee (where required) unless authorised to do so.

SYNOPSIS

Study Title	A systems dynamics model to measure the impact of third party reverse logistics providers on closed loop supply chain performance	
Internal ref. no. / short title		
Study Design	Case studies, experiments, simulation modelling	
Study Participants	Company employees involved in the reverse logistics process, manufacturing, remanufacturing	
Planned Number of Cases	Minimum number of 2 case studies as it is a comparative research	
Planned Study Period	For the whole thesis, 3 years, but for case studies maximum of 5 months, minimum 2 months	
	Objectives	Outcome Measures
Primary		
Secondary		

BACKGROUND AND RATIONALE

This PhD thesis aims to explore the role played by 3PLs in reverse logistics and closed loop supply chains. The thesis measures the Bullwhip Effect and some supply chain performance measures in the closed loop supply chain.

There is a growing interest for the Bullwhip effect and Closed Loop Supply Chains but research on the two topics combined together is very little. In an invited review on the Bullwhip Effect, Wang (2016) in identifying current trends of the phenomenon, advocated for measurement of the Bullwhip effect in sustainable supply chains. Closed loop Supply Chains are a part of sustainable supply chains and product returns do have an impact on the Bullwhip Effect of the forward chain in which they are returning to.

Considering the power given to consumers nowadays as well as the strict environmental legislations in some parts of the world, the Closed Loop Supply Chain is not an option for some organisations but it is a must. Given its growing importance and necessity it is necessary for Original Equipment Manufacturers to find the best operating modes for their closed loop supply chains. In the search for these best operating modes, some OEMs cannot afford to build new infrastructure and they do not have the technologies necessary for closed loop supply chains, so they form contracts and ventures with third parties for assistance in activities of the reverse supply chain. As beneficial as this may be, the delays introduced by introducing more echelons in a supply chain, may impact the Bullwhip Effect in the closed loop supply chain. This research aims to investigate the impact of third parties on the Bullwhip Effect in closed loop supply chains.

By means of a multiple case study research, the research will try to reveal the state of the art in terms of the use of third parties in closed loop supply chains, that is the main activities that they focus on, the types of relationships and agreements that they establish with OEMs at the same time measuring the impact of their presence on closed loop supply chain performance.

AIM AND OBJECTIVES

Aim/Research Questions	Objectives
How would the Bullwhip effect and supply chain performance in the forward chain be affected by introducing a closed loop chain consisting of a retailer returning products for product upgrades and one for remanufacturing end of use products? What specific activities do third party reverse logistics providers carry out in a closed loop supply chain and how do they coordinate the activities of the forward and reverse chain in the supply chain?	Get information on the activities in the forward chain in terms of supply chain structure, demand pattern, demand forecasting method, the inventory control methods, desired inventory levels, production capacities. Interview parties involved directly involved with the reverse logistics system to know if a company employs third parties or not. If they do, the research needs to know what specific activities they are employed for in the closed loop supply chain. The research aims to give a background of the organisation and its introduction of the closed loop supply chain as well as the problems and benefits experienced as a result of the closed loop system.
How would the supply chain performance measures such as the BWE, lead time and customer service level in a closed loop system change if a 3PL carries out RL activities?	Make a comparison of supply chain performance between organisations that carry out their own reverse logistics activities and those that employ third parties, this will be done during the data analysis phase.

PARTICIPANT IDENTIFICATION

Study Participants

Participants in this research are mostly employees in organisations (OEMs) who have particular knowledge of the supply chain activities of the organisation as well as reverse logistics operations carried out by the organisation. List of participants include but is not limited to;

- Production managers
- Operations managers
- Production planners
- Supply chain planners
- Inventory controllers

Some participants may have different titles from the usual known titles but may have knowledge of the operations under study.

Inclusion Criteria

Case studies suitable for this research need to be strictly closed loop supply chains as described by Asif (2012) and Prahinski (2006), this means companies in which "the product returns to the OEM and that they can lead to a business to make adjustments in product design and procurement practices, the core is collected by the OEM or the third party remanufacturer that acts as the supplier to the OEM, the core enters and is used in the main stream of a manufacturing forward material flow and the remanufactured product is sold in the same way as the new one, i.e. the remanufactured product is not considered as a different product variant and order and supply is not handled separately".

In other words, the research only focuses on those cases in which the process of reverse logistics has an impact on the forward chain of the OEM and not on those supply chains where one OEM forms their supply chain at the end of another's supply chain.

Exclusion Criteria

As explained in the inclusion criteria, open loop supply chains are not included in this research. Once again Asif (2012) stated some reasons for a supply chain not to be classified as a closed loop supply chain;

- The recovered cores do not enter the main stream of the forward supply chain.
- The recovered contents of the original products are used by other firms to manufacture products that serve a different purpose.

These types of supply chains are excluded as case studies for this research.

The research does not look at processing industries, that is those industries that do not manufacture discrete products, for example steel manufacturers, where component recovery, component reuse and remanufacturing cannot be performed but only recycling is possible. This is because mostly when recycling alone is possible it tends to be an open loop supply chain, but if recycling alone is possible and the supply chain can be termed "closed loop" then it might be included depending on the scarcity of case studies in this field.

The research also excludes case studies that only focus on manufacturing and commercial returns (i.e. returns due to quality and product recalls, or returnable containers and bottles)

STUDY ACTIVITIES

Recruitment

In recruiting participants for the case studies, the researchers approached company management who will approve the research and then assign someone to assist in all the necessary activities and questions. The guide will also assist in identifying individuals who can assist in the research.

Informed Consent

According to the ethical clearance requirements of Stellenbosch University, the company writes a letter of consent to the participants before the research begins. During the course of the research both the participant and company management will sign the interview question document and other related documents to verify if their answers are correctly represented.

The participant and company management must sign and date the latest approved version of the Informed Consent form before any study specific activities are undertaken.

Written and verbal versions of the Participant Information and Informed Consent will be presented to the participants detailing the exact nature of the study, what it will involve for the participant, the implications and constraints of the protocol, any risks involved in taking part. It will be clearly stated that the participant is free to withdraw from the study at any time for any reason without prejudice to future care, and with no obligation to give the reason for withdrawal.

The research will conduct initial pilot studies this means that more than one visit to a company will be carried out and this will be clearly stated in the interview questions for the research.

Withdrawal of participants will lead to their data being excluded from the research and if there are other case studies, the participants can be replaced. Because of the scarcity of closed loop supply chains, not all participants who withdraw may be replaced. The reasons for withdrawal will also be stated in the report file for the case studies.

Field procedures

the first thing to do is to contact the potential interviewees.

set up a meeting

Take two recording devices for backup

Test it before the meeting

Before the meeting, the researcher identifies relevant information on the web site of the company and potentially in some important reports of the company.

Interviewees can remain anonymous but the organisation cannot be anonymous. The thesis will give a brief history on the organisation and their closed loop supply chain activities.

Case study questions

Interview Questions

Introduction

1. What is the name of your organisation?
2. What products does your company manufacture?
3. How would you classify your organisation?

- ☐ Small (0-500 employees)
- ☐ Medium (500-1000 employees)
- ☐ Large (above 1000 employees)

4. What is your role in the company?

About the Supply Chain

5. How best can you describe your demand pattern?
6. What is your production capacity?
7. How do you usually forecast demand?
8. Do you maintain specific levels of stock?
9. How much time do you usually need to adjust your inventory to desired levels?
10. How much time do you usually need to distribute products to customers?
11. How much orders do you usually expect from your customers periodically?
12. How many components would you say make up your product?

Closed Loop Supply Chain Management

13. How long is your product's useful life?
14. How long do customers usually keep products before deciding to return them?
15. Of all your sold products, what percentage do you usually successfully collect from customers?
16. Who collects and transports used products?
17. Approximately how much products do you expect to be collected periodically?
18. Is there a capacity limit to the collection of used products?
19. Who carries out the inspection and disposition of the products?
20. How long does it take to inspect a product to determine its usefulness?
21. Which of the following disposition strategies is your organisation involved in?

- ☐ Product reuse
- ☐ Product remanufacture
- ☐ Component reuse
- ☐ Component remanufacture
- ☐ Recycling

22. Out of your inspected products, what percentage is usually suitable for direct reuse?
23. What percentage is usually suitable for product remanufacturing?
24. If you reuse components, what percentage of the components is usually suitable for reuse?
25. What percentage of the components is usually suitable for remanufacturing?
26. Are there any capacity limits on the remanufacture of products and components?
27. What time does your company usually take to remanufacture products or components?

General Questions

28. What do you think are the benefits of incorporating a closed loop supply chain in your organisation?
29. Are there any problems with the closed loop system?

30. Are there any parts of the closed loop system that you think need improvement?
31. Any recommendations for the future operation of the closed loop system?

Outline of case study report

1. Organisational context of the company.
2. Description of the closed loop system structure and relationship between parties.
3. Reverse Logistics practices of the company.
4. Closed loop supply chain performance measurement.
5. Managerial implications of these performance measurement (advantages and challenges).
6. Recommendations by participant

Appendix C: Statistical analyses outputs from Minitab

Minitab 16 software was used for analysing the results from the simulations. Most Tables output from Minitab can be viewed under this appendix.

Table C1: Test for significance of factors for BWE wholesaler for electric vehicle batteries under a Normal distribution

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DI adjustment time	4	27492	11881	2970	0.61	0.656
DI cover time	4	11396	6488	1622	0.33	0.856
WI adjustment time	4	331355	318309	79577	16.34	0.000
WI cover time	4	84816	97888	24472	5.03	0.001
RI adjustment time	4	536203	528074	132018	27.11	0.000
RI cover time	4	56763	56763	14191	2.91	0.021
Error	1179	5741346	5741346	4870		
Total	1203	6789371				

Table C2: Test for significance of factors for BWE retailer for electric vehicle batteries under a Normal distribution

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DI adjustment time	4	20332	15647	3912	0.85	0.491
DI cover time	4	15471	14377	3594	0.78	0.535
WI adjustment time	4	18267	14410	3602	0.79	0.534
WI cover time	4	14786	15792	3948	0.86	0.486
RI adjustment time	4	61763	62758	15689	3.43	0.009
RI cover time	4	16337	16337	4084	0.89	0.468
Error	1179	5399982	5399982	4580		
Total	1203	5546939				

Table C3: Correlation test for electric vehicle batteries under a Poisson distribution

	DI adjustment time	DI cover time	WI adjustment time	WI cover time	RI adjustment time	RI cover time	BWE distributor	BWE wholesaler
DI cover time	0.000 **0.989**							
WI adjustment time	-0.000 **0.990**	-0.006 **0.852**						
WI cover time	0.003 **0.926**	0.004 **0.915**	0.003 **0.936**					
RI adjustment time	-0.001 **0.979**	-0.002 **0.947**	0.002 **0.947**	-0.001 **0.968**				
RI cover time	-0.007 **0.826**	-0.006 **0.847**	0.006 **0.847**	0.007 **0.827**	-0.003 **0.921**			
BWE distributor	-0.198 **0.000**	0.148 **0.000**	-0.175 **0.000**	0.149 **0.000**	0.265 **0.000**	0.066 **0.048**		
BWE wholesaler	-0.026 **0.432**	0.007 **0.239**	-0.263 **0.000**	0.239 **0.000**	-0.413 **0.000**	0.113 **0.001**	0.727 **0.000**	
BWE retailer	-0.009 **0.794**	0.019 **0.567**	0.016 **0.642**	0.007 **0.843**	-0.666 **0.000**	0.381 **0.000**	0.422 **0.000**	0.598 **0.000**
Cell Contents: Pearson correlation **P-Value**								

Table C4: Significance test for BWE wholesaler for electric vehicle batteries under a Poisson distribution

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DI adjustment time	4	25317	9910	2477	0.52	0.721
DI cover time	4	13085	8205	2051	0.43	0.787
WI adjustment time	4	334529	321607	80402	16.87	0.000
WI cover time	4	85708	98356	24589	5.16	0.000
RI adjustment time	4	535174	526681	131670	27.62	0.000
RI cover time	4	58950	58950	14738	3.09	0.015
Error	1177	5610250	5610250	4767		
Total	1203	6789371				

Table C5: Significance test for BWE retailer for electric vehicle batteries under a Poisson distribution

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DI adjustment time	4	21070	16322	3190	0.89	0.499
DI cover time	4	15717	14635	4080	0.80	0.469
WI adjustment time	4	17658	13895	3659	0.76	0.526
WI cover time	4	14762	15688	3474	0.86	0.553
RI adjustment time	4	61933	62993	3922	3.44	0.008
RI cover time	4	16591	16591	15748	0.91	0.460
Error	1177	5393601	5393601	4582		
Total	1203	5546939				

Table C6: Significance test for BWE distributor for kitchen appliances under a Normal distribution

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DI adjustment time	3	132975	131652	43884	21.79	0.000
DI cover time	3	73071	73174	24391	12.11	0.000
WI adjustment time	3	124051	124615	41538	20.62	0.000
WI cover time	3	39274	39529	13176	6.54	0.000
RI adjustment time	3	156001	156395	52132	25.88	0.000
RI cover time	3	61590	61590	20530	10.19	0.000
Error	879	1770591	1770591	2014		
Total	899	2360570				

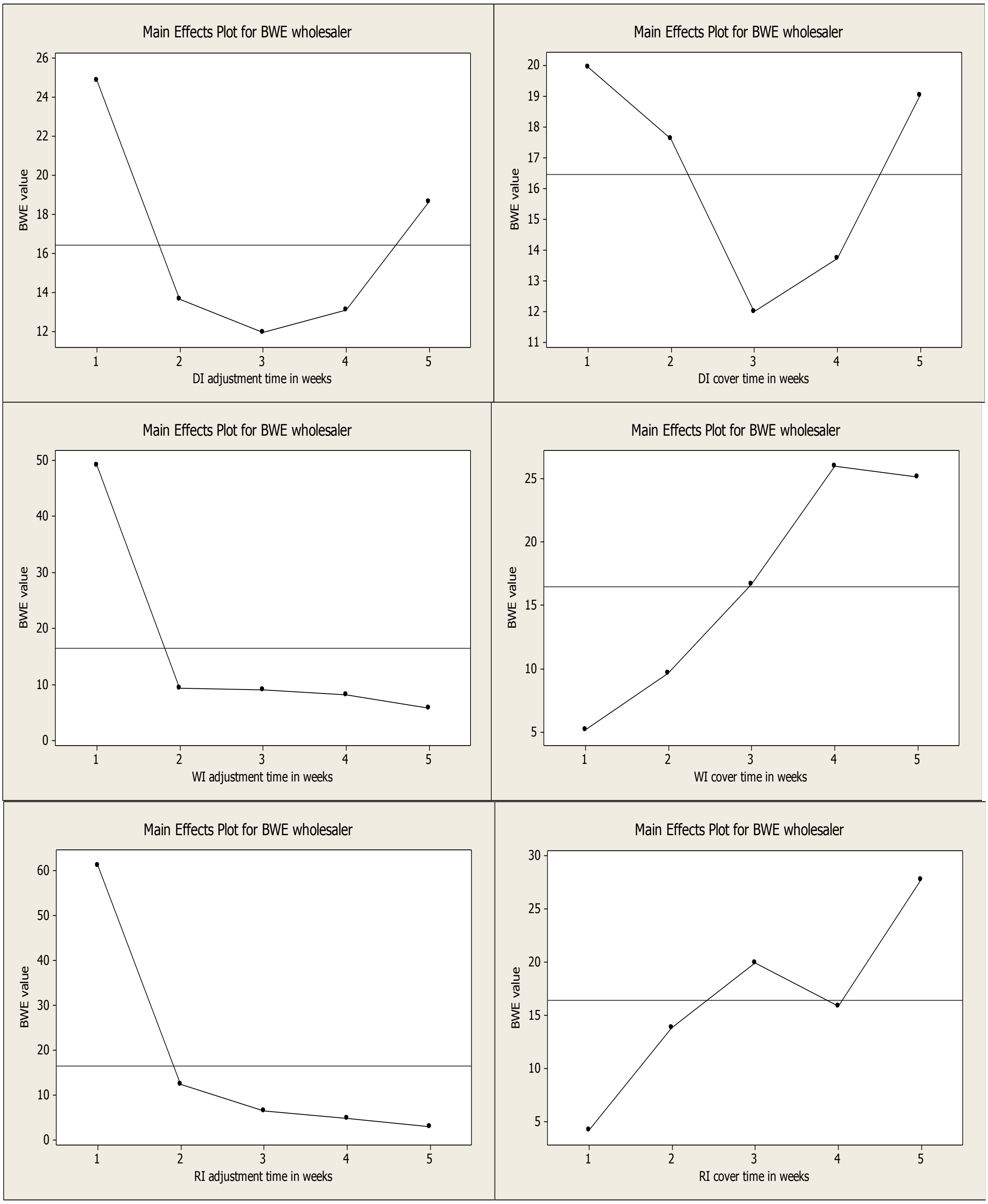


Figure C1: Main effects plot for BWE wholesaler for electric vehicle batteries under a Poisson distribution

Table C7: Correlation test for kitchen appliances under a normal distribution

	DI adjustment time	DI cover time	WI adjustment time	WI cover time	RI adjustment time	RI cover time	BWE distributor	BWE wholesaler
DI cover time	0.004 **0.902**							
WI adjustment time	-0.001 **0.965**	0.001 **0.979**						
WI cover time	-0.003 **0.927**	0.005 **0.873**	0.004 **0.916**					
RI adjustment time	-0.003 **0.940**	-0.004 **0.905**	0.003 **0.926**	0.002 **0.958**				
RI cover time	0.007 0.845	0.001 **0.968**	-0.001 **0.968**	0.000 **1.000**	0.002 **0.957**			
BWE distributor	-0.021 **0.000**	-0.211 **0.000**	0.165 **0.000**	0.128 **0.000**	-0.218 **0.000**	0.159 **0.000**		
BWE wholesaler	-0.026 **0.438**	-0.011 **0.735**	-0.001 **0.973**	0.223 **0.000**	-0.444 **0.000**	0.252 **0.000**	0.667 **0.000**	
BWE retailer	-0.005 **0.879**	0.016 **0.638**	-0.025 **0.457**	-0.004 **0.916**	-0.629 **0.000**	0.524 **0.000**	0.336 **0.000**	0.641 **0.000**
Cell Contents: Pearson correlation **P-Value**								

Table C8: Significance test for BWE distributor for kitchen appliances under a lognormal distribution

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DI adjustment time	3	132975	131652	43884	21.79	0.000
DI cover time	3	73071	73174	24391	12.11	0.000
WI adjustment time	3	124051	124615	41538	20.62	0.000
WI cover time	3	39274	39529	13176	6.54	0.000
RI adjustment time	3	156001	156395	52132	25.88	0.000
RI cover time	3	61590	61590	20530	10.19	0.000
Error	879	1770591	1770591	2014		
Total	899	2360570				

Table C10: Significance test for BWE wholesaler for kitchen appliances under a lognormal distribution

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DI adjustment time	3	14.6	11.9	4.0	0.11	0.955
DI cover time	3	114.7	116.5	38.8	1.06	0.367
WI adjustment time	3	4999.4	5052.4	1684.1	45.77	0.000
WI cover time	3	3097.6	3128.1	1042.7	28.33	0.000
RI adjustment time	3	16432.4	16454.4	5484.8	149.05	0.000
RI cover time	3	3961.2	3961.2	1320.4	35.88	0.000
Error	879	32346.2	32346.2	36.8		
Total	899	61073.6				

Table C11: Significance test for BWE retailer for kitchen appliances under a lognormal distribution

Source	DF	Seq SS	Adj SS	Adj MS	F	P
DI adjustment time	3	21.4	19.5	6.5	0.81	0.489
DI cover time	3	23.4	26.5	8.8	1.10	0.348
WI adjustment time	3	94.2	107.5	35.8	4.46	0.004
WI cover time	3	10.3	8.7	2.9	0.36	0.782
RI adjustment time	3	16161.3	16200.2	5400.1	672.95	0.000
RI cover time	3	9065.1	9065.1	3021.7	376.56	0.000
Error	879	7053.5	7053.5	8.0		
Total	899	32431.2				

Table C9: Correlation test for kitchen appliances under a lognormal distribution

	DI adjustment time	DI cover time	WI adjustment time	WI cover time	RI adjustment time	RI cover time	BWE distributor	BWE wholesaler
DI cover time	0.004 **0.902**							
WI adjustment time	-0.001 **0.965**	0.001 **0.979**						
WI cover time	-0.003 **0.927**	0.005 **0.873**	0.004 **0.916**					
RI adjustment time	-0.003 **0.940**	-0.004 **0.905**	0.003 **0.926**	0.002 **0.958**				
RI cover time	0.007 0.845	0.001 **0.968**	-0.001 **0.968**	0.000 **1.000**	0.002 **0.957**			
BWE distributor	-0.021 **0.000**	-0.211 **0.000**	0.165 **0.000**	0.128 **0.000**	-0.218 **0.000**	0.159 **0.000**		
BWE wholesaler	-0.026 **0.438**	-0.011 **0.735**	-0.001 **0.973**	0.223 **0.000**	-0.444 **0.000**	0.252 **0.000**	0.667 **0.000**	
BWE retailer	-0.005 **0.879**	0.016 **0.638**	-0.025 **0.457**	-0.004 **0.916**	-0.629 **0.000**	0.524 **0.000**	0.336 **0.000**	0.641 **0.000**
Cell Contents: Pearson correlation **P-Value**								

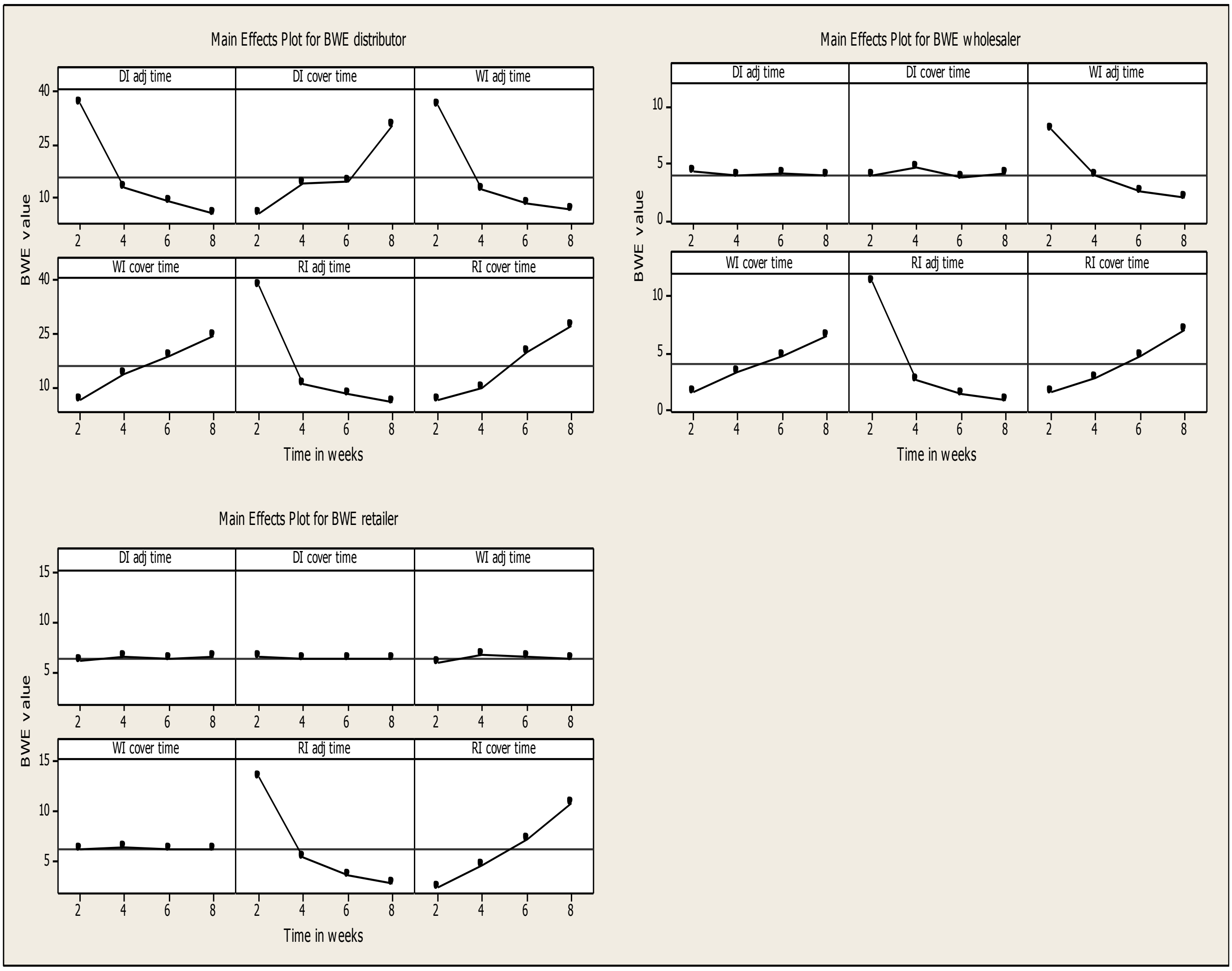


Figure C2: Main effects plots for kitchen appliances under a lognormal distribution

Table C12: Test for significance of factors for BWE distributor for electric vehicles under a normally distributed demand and no capacity limits

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	516.6	516.6	172.2	0.76	0.523
Remanufacturing percent	3	1079.6	1079.6	359.9	1.58	0.204
Reprocess time	3	1101.8	1101.8	367.3	1.62	0.197
Error	54	12277.8	12277.8	227.4		
Total	63	14975.8				

Table C13: Least squares means for electric vehicle batteries under normally distributed demand with no capacity limits

	BWE distributor		BWE wholesaler		BWE retailer	
Residence time	Mean	SE Mean	Mean	SE Mean	Mean	SE Mean
4	89.146	3.7697	18.155	0.9418	3.491	0.2026
8	91.701	3.7697	18.419	0.9418	3.567	0.2026
16	94.521	3.7697	19.341	0.9418	3.891	0.2026
24	96.665	3.7697	20.649	0.9418	4.448	0.2026
Remanufacturing percent						
25	99.391	3.7697	20.491	0.9418	4.053	0.2026
50	93.050	3.7697	18.838	0.9418	3.663	0.2026
75	88.050	3.7697	18.256	0.9418	3.823	0.2026
100	91.542	3.7697	18.979	0.9418	3.859	0.2026
Reprocessing time						
0.300	99.524	3.7697	20.536	0.9418	4.060	0.2026
0.375	91.843	3.7697	18.468	0.9418	3.638	0.2026
0.450	88.016	3.7697	17.996	0.9418	3.610	0.2026
0.600	92.651	3.7697	19.564	0.9418	4.089	0.2026

Table C14: Correlation test for electric vehicle batteries under a normally distributed demand and no capacity limits

	Residence time	Remanufacturing percent	Reprocessing time	BWE distributor	BWE wholesaler
Remanufacturing percent	0.000 ***1.000***				
Reprocess time	0.000 ***1.000***	0.000 ***1.000***			
BWE distributor	0.183 ***0.148***	-0.209 ***0.098***	-0.139 ***0.273***		
BWE wholesaler	0.253 ***0.044***	-0.150 ***0.237***	-0.056 ***0.659***	0.955 ***0.000***	
BWE retailer	0.422 ***0.001***	-0.054 ***0.672***	0.052 ***0.683***	0.757 ***0.000***	0.908 ***0.000***
Cell contents: correlation ***p-values***					

Table C15: Test for significance of factors for BWE wholesaler for electric vehicle batteries under a normally distributed demand and no capacity limits

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	60.91	60.91	20.30	1.43	0.244
Remanufacturing percent	3	43.57	43.57	14.52	1.02	0.390
Reprocess time	3	62.21	62.21	20.74	1.46	0.235
Error	54	766.39	766.39	14.19		

Total	63	933.08				

Table C16: Test for significance of factors for BWE retailer for electric vehicle batteries under a normally distributed demand and no capacity limits

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	9.0810	9.0810	3.0270	4.61	0.006
Remanufacturing percent	3	1.2316	1.2316	0.4105	0.63	0.602
Reprocess time	3	3.2560	3.2560	1.0853	1.65	0.188
Error	54	35.4483	35.4483	0.6564		
Total	63	49.0168				

Table C17: Test for significance of factors for BWE distributor for kitchen appliances under a lognormal demand distribution and no capacity limits with external returns

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	17.642	17.642	5.881	1.33	0.274
Remanufacturing percent	3	2.561	2.561	0.854	0.19	0.901
Reprocess time	3	4.715	4.715	1.572	0.36	0.785
Error	54	238.673	238.673	4.420		
Total	63	263.591				

Table C18: Least squares means for kitchen appliances under a lognormal demand distribution with no capacity limits and external returns

	BWE distributor		**BWE wholesaler**		**BWE retailer**	
Residence time	**Mean**	**SE Mean**	**Mean**	**SE Mean**	**Mean**	**SE Mean**
12	2.2793	0.52599	0.4655	0.9505	0.2102	0.01248
36	2.0234	0.52599	0.4342	0.9505	0.2285	0.01248
60	0.8996	0.52599	0.2148	0.9505	0.1820	0.01248
96	1.5504	0.52599	0.3431	0.9505	0.2064	0.01248
Remanufacturing percent						
25	1.6158	0.52599	0.3534	0.9505	0.2041	0.01248
50	2.0048	0.52599	0.4187	0.9505	0.2106	0.01248
75	1.6774	0.52599	0.3586	0.9505	0.2106	0.01248
100	1.4547	0.52599	0.3269	0.9505	0.2019	0.01248
Reprocessing time						
0.004	2.1299	0.52599	0.4470	0.9505	0.2228	0.01248
0.008	1.4193	0.52599	0.3068	0.9505	0.1913	0.01248
0.013	1.6801	0.52599	0.3626	0.9505	0.1982	0.01248
0.210	1.5233	0.52599	0.3413	0.9505	0.2149	0.01248

Table C19: Correlation test for kitchen appliances under a lognormal demand distribution and no capacity limits with external returns

	Residence time	Remanufacturing percent	Reprocessing time	BWE distributor	BWE wholesaler
Remanufacturing percent	0.000 ***1.000***				
Reprocess time	0.000 ***1.000***	0.000 ***1.000***			
BWE distributor	-0.164 ***0.195***	-0.045 ***0.726***	-0.049 ***0.698***		
BWE wholesaler	-0.160 ***0.207***	-0.042 ***0.739***	-0.039 ***0.760***	0.997 ***0.000***	
BWE retailer	-0.112 ***0.379***	-0.015 ***0.907***	0.086 ***0.498***	0.678 ***0.000***	0.722 ***0.000***
Cell contents: correlation ***p-values***					

Table C20: Test for significance of factors for BWE wholesaler for kitchen appliances under a lognormal demand distribution and no capacity limits with external returns

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	0.6067	0.6067	0.2022	1.40	0.253
Remanufacturing percent	3	0.0721	0.0721	0.0240	0.17	0.919
Reprocess time	3	0.1710	0.1710	0.0570	0.39	0.758
Error	54	7.8055	7.8055	0.1445		
Total	63	8.6553				

Table C21: Test for significance of factors for BWE distributor for kitchen appliances under a lognormal demand distribution and no capacity limits without external returns

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	10.394	10.394	3.465	1.05	0.013
Remanufacturing percent	3	4.930	4.930	1.643	0.50	0.043
Reprocess time	3	16.856	16.856	5.619	1.71	0.176
Error	54	177.677	177.677	3.290		
Total	63	209.857				

Table C22: Least squares means for kitchen appliances under a lognormal demand distribution with no capacity limits without external returns

	BWE distributor		**BWE wholesaler**		**BWE retailer**	
Residence time	**Mean**	**SE Mean**	**Mean**	**SE Mean**	**Mean**	**SE Mean**
12	1.7651	0.45348	0.3945	0.10259	0.2179	0.02462
36	2.1417	0.45348	0.5147	0.10259	0.2667	0.02462
60	2.4761	0.45348	0.6262	0.10259	0.3299	0.02462
96	2.8548	0.45348	0.7729	0.10259	0.4003	0.02462
Remanufacturing percent						
25	1.8535	0.45348	0.4762	0.10259	0.2888	0.02462
50	2.5787	0.45348	0.6754	0.10259	0.3423	0.02462
75	2.4746	0.45348	0.6288	0.10259	0.3186	0.02462
100	2.3309	0.45348	0.5278	0.10259	0.2651	0.02462
Reprocessing time						
0.004	2.3092	0.45348	0.5473	0.10259	0.2880	0.02462
0.008	2.7509	0.45348	0.6873	0.10259	0.3304	0.02462
0.013	1.4719	0.45348	0.3747	0.10259	0.2588	0.02462
0.210	2.7058	0.45348	0.6989	0.10259	0.3375	0.02462

Table C23: Correlation test for kitchen appliances under a lognormal demand distribution and no capacity limits without external returns

	Residence time	**Remanufacturing percent**	**Reprocessing time**	**BWE distributor**	**BWE wholesaler**
Remanufacturing percent	0.000 ***1.000***				
Reprocess time	0.000 ***1.000***	0.000 ***1.000***			
BWE distributor	0.221 ***0.039***	0.082 ***0.520***	0.120 ***0.345***		
BWE wholesaler	0.324 ***0.009***	0.028 ***0.825***	0.158 ***0.213***	0.967 ***0.000***	
BWE retailer	0.563 ***0.000***	-0.087 ***0.494***	0.157 ***0.215***	0.706 ***0.000***	0.848 ***0.000***
Cell contents: correlation ***p-values***					

Table C24: Test for significance of factors for BWE distributor for electric vehicle batteries under a Poisson demand distribution and collection capacity limits

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	4	84880	87385	21846	38.83	0.000
Remanufacturing percent	3	11784	10465	3488	6.20	0.000
Reprocess time	4	2044	2366	591	1.05	0.382
Collection capacity	2	61320	61320	30660	54.50	0.000
Error	178	100143	100143	227.4		
Total	191	260170				

Table C25: Least squares means for electric vehicle batteries under Poisson demand distribution with collection capacity limits

	BWE distributor		**BWE wholesaler**		**BWE retailer**	
Residence time	**Mean**	**SE Mean**	**Mean**	**SE Mean**	**Mean**	**SE Mean**
4	124.693	5.4902	28.569	1.2807	5.875	0.2118
8	143.926	5.2966	33.264	1.2355	6.575	0.2044
16	173.607	5.4125	40.145	1.2625	7.794	0.2088
24	178.704	5.2062	41.356	1.2144	8.043	0.2009
Remanufacturing percent						
25	146.084	4.8461	33.335	1.1328	6.876	0.1874
50	149.360	4.8994	34.399	1.1429	7.051	0.1890
75	161.948	4.5994	37.773	1.0729	7.232	0.1775
100	162.899	4.6040	37.673	1.0739	7.018	0.1776
Reprocessing time						
0.300	148.707	3.9209	34.371	6.862	6.862	0.1513
0.375	156.773	3.996	36.140	7.118	7.118	0.1543
0.450	149.128	3.8351	34.420	6.824	6.824	0.1480
0.600	152.621	3.9739	34.500	6.772	6.772	0.1533
Collection capacity						
65	129.657	4.1444	29.433	6.338	6.338	0.1599
75	166.501	4.5518	38.636	7.348	7.348	0.1756
80	169.061	4.5445	39.316	7.447	7.447	0.1753

Table C26: Correlation test for electric vehicle batteries under a Poisson demand distribution and collection capacity limits

	Residence time	Remanufacturing percent	Reprocessing time	Collection capacity	BWE distributor	BWE wholesaler
Remanufacturing percent	-0.002 ***0.973***					
Reprocess time	0.004 ***0.951***	-0.041 ***0.573***				
Collection capacity	-0.009 ***0.906***	0.011 ***0.878***	0.041 ***0.575***			
BWE distributor	0.540 ***0.000***	0.204 ***0.005***	0.010 ***0.894***	0.463 ***0.000***		
BWE wholesaler	0.530 ***0.000***	-0.222 ***0.237***	-0.023 ***0.746***	0.484 ***0.000***	0.995 ***0.000***	
BWE retailer	0.610 ***0.000***	0.063 ***0.385***	-0.050 ***0.492***	0.353 ***0.000***	0.945 ***0.000***	0.948 ***0.000***
Cell contents: correlation ***p-values***						

Table C27: Test for significance of factors for BWE distributor for kitchen appliances under a lognormal demand distribution with collection capacity limits and no external returns

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	3	21.052	20.434	6.811	3.03	0.031
Remanufacturing percent	3	2.088	2.033	0.678	0.30	0.824
Reprocess time	3	4.211	4.126	1.375	0.61	0.608
Collection capacity	2	18.811	18.811	9.406	4.19	0.017
Error	180	404.014	404.014	2.245		
Total	191	450.096				

Table C28: Least squares means for electric kitchen appliances under lognormal demand distribution with collection capacity limits and no external returns

	BWE distributor		BWE wholesaler		BWE retailer	
Residence time	**Mean**	**SE Mean**	**Mean**	**SE Mean**	**Mean**	**SE Mean**
12	1.6259	0.216243	0.3808	0.041146	0.2261	0.010536
36	1.7125	0.223593	0.4380	0.045245	0.2775	0.010894
60	2.4515	0.210078	0.5825	0.039973	0.3061	0.010236
96	1.8945	0.216313	0.5348	0.041160	0.3459	0.010540
Remanufacturing percent						
25	1.8953	0.216708	0.4612	0.041235	0.2673	0.010653
50	2.0812	0.216402	0.5182	0.041177	0.2988	0.010444
75	1.9134	0.216243	0.4951	0.041146	0.2993	0.010536
100	1.7945	0.216243	0.4615	0.041146	0.2902	0.010536
Reprocessing time						
0.004	1.9565	0.218632	0.4850	0.041601	0.2798	0.010653
0.008	2.0627	0.214350	0.5153	0.040786	0.3001	0.010444
0.013	1.6766	0.216243	0.4374	0.041146	0.2832	0.010536
0.210	1.9887	0.216337	0.4983	0.041164	0.2925	0.010541
Collection capacity						
4000	2.3622	0.187392	0.5715	0.035657	0.3040	0.009130
6000	1.6707	0.186132	0.4328	0.035417	0.2810	0.009069
8000	1.7304	0.188823	0.4476	0.035929	0.2817	0.009200

Table C29: Correlation test for electric kitchen appliances under lognormal demand distribution with collection capacity limits and no external returns

	Residence time	Remanufacturing percent	Reprocessing time	Collection capacity	BWE distributor	BWE wholesaler
Remanufacturing percent	-0.013 ***0.862***					
Reprocess time	0.002 ***0.976***	-0.000 ***0.996***				
Collection capacity	-0.014 ***0.845***	0.003 ***0.969***	0.003 ***0.962***			
BWE distributor	0.097 ***0.181***	-0.043 ***0.557***	0.024 ***0.738***	-0.173 ***0.016***		
BWE wholesaler	0.215 ***0.003***	-0.017 ***0.815***	0.027 ***0.711***	-0.177 ***0.014***	0.967 ***0.000***	
BWE retailer	0.505 ***0.000***	0.084 ***0.249***	0.025 ***0.730***	-0.116 ***0.108***	0.455 ***0.000***	0.652 ***0.000***

Cell contents:
correlation
p-values

Table C30: Test for significance of factors for BWE distributor for electric vehicle batteries under a Poisson demand distribution and remanufacturing capacity limits

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Residence time	4	56020	55809	13952	6.43	0.000
Remanufacturing percent	3	4366	4506	1502	0.69	0.558
Reprocess time	4	4924	4866	1216	0.56	0.692
Remanufacturing capacity	2	5733	5733	2867	1.32	0.270
Error	178	386507	386507	2171		
Total	191					

Table C31: Correlation test for electric vehicle batteries under a Poisson demand distribution and remanufacturing capacity limits

	Residence time	Remanufacturing percent	Reprocessing time	Remanufact capacity	BWE distributor	BWE wholesaler
Remanufacturing percent	-0.002 ***0.973***					
Reprocess time	0.001 ***0.985***	-0.035 ***0.632***				
Remanufacturing capacity	-0.009 ***0.906***	0.011 ***0.878***	0.020 ***0.784***			
BWE distributor	0.276 ***0.000***	-0.085 ***0.240***	-0.051 ***0.483***	-0.014 ***0.844***		
BWE wholesaler	0.203 ***0.005***	-0.120 ***0.098***	-0.049 ***0.504***	-0.016 ***0.829***	0.992 ***0.000***	
BWE retailer	0.278 ***0.000***	-0.197 ***0.006***	-0.035 ***0.627***	-0.017 ***0.818***	0.982 ***0.000***	0.990 ***0.000***
Cell contents: correlation ***p-values***						

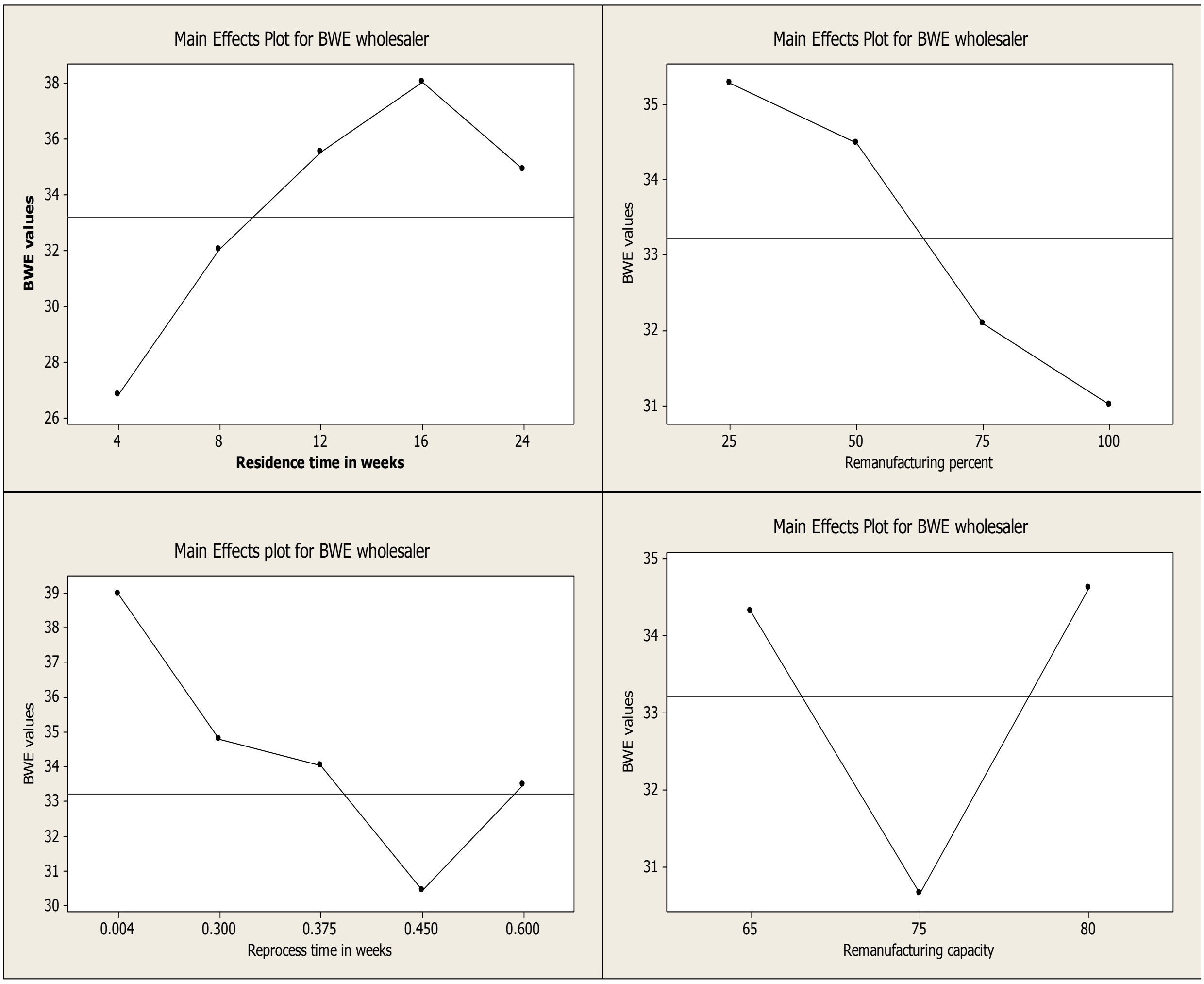


Figure C3: Main effects plots for BWE wholesaler for electric vehicle batteries under a Poisson demand distribution with remanufacturing capacity limits only

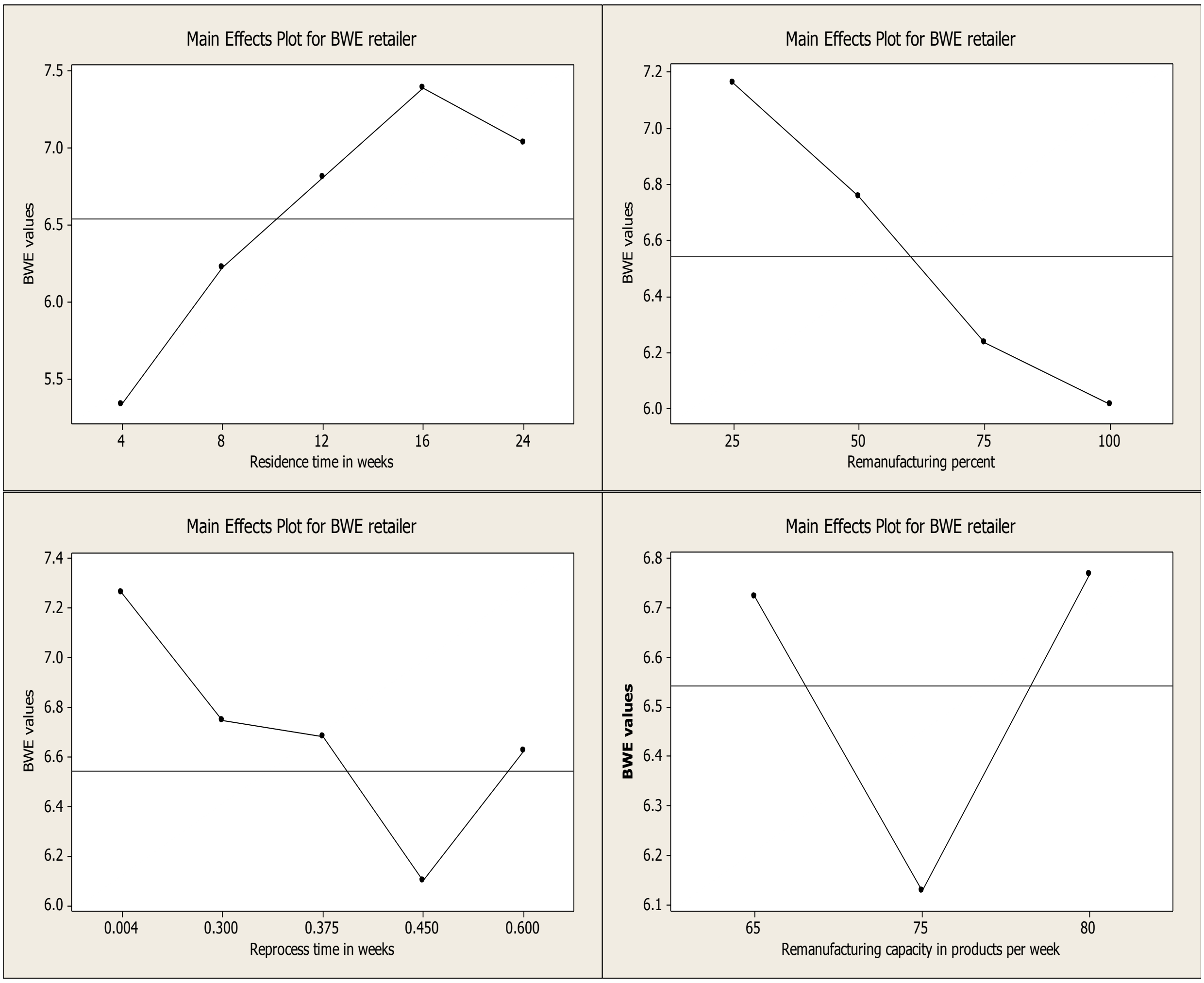


Figure C4: Main effects plots for BWE retailer for electric vehicle batteries under a Poisson demand distribution with remanufacturing capacity limits only

Appendix D: Stocks, Flows and Auxiliaries of the simulation models

The appendix lists the stocks, flows and auxiliary variables as they are represented and used in the simulation model.

Table D1: Stocks

Stock	Definition	Stock	Definition
RAW MATERIALS	Inventory of raw materials	COMP INV	Inventory of components used for production
Serviceable inv	Inventory of finished products	Distri inv	Inventory stocked by the distributor
Retailer inv	Inventory stocked by the retailer	Distri orders backlog	Inventory of orders missed by the distributor in a certain period, satisfied in the next period
Retail order backlog	Inventory of orders missed by the retailer satisfied in the next period	Reje pro for reuse	Inventory of products that have been inspected and found unsuitable for reuse
Collected products	Inventory of used products that the manufacturer successfully collects	Prod for cannibalisation	Inventory of products found to be unsuitable for remanufacturing and are meant to be torn down
Prdcts for reman	Inventory of products inspected and found suitable for remanufacturing	Prdcts reje for reman	Inventory of products found unsuitable for remanufacturing
Inv of comp from reje prdcts	Inventory of components obtained from products rejected for remanufacturing	Comp reje for dir reuse	Inventory of components that have been inspected and cannot be reused directly
Controllable disposal	Inventory of products and components that have been found to be useless and are disposed of by the manufacturer.	Reman backlog	Inventory of products not remanufactured to be remanufactured in the next period.

Table D2: Flow variables

Flow variable	**Definition**	**Flow variable**	**Definition**
COMP PROD RATE	The number of components produced per unit time	Comp used for product prdn	The number of components taken from the components inventory and used for the production of the products
Prdct prdn rate	The number of products produced per unit time	Shipment to distri	The number of products shipped to distributor per unit time
Retail sales	The amount of products sold by the retailer per unit time	Retail orders	The number of products that the retailer orders from the distributor per unit time
Ret backlog redu	The rate at which the retailer tries to reduce order backlogs in each period	Distri order	The number of orders that the distributor orders from the supplier per unit time
Distri backlog redu	The rate at which the distributor tries to reduce order backlogs in each time period	Uncontr disposal rate	The amount of products disposed of out of the manufacturer's control per unit time
Comp acce rate for dir reuse	The amount of components accepted for reuse per unit time	Comp rem rate	The number of components that can be remanufactured per unit time
Raw mat reco rate	The amount of raw materials that can be recovered from rejected products per unit time	Comp reje rate for dir reuse	The amount of components that are rejected for direct reuse per unit time
Comp from reje products	The rate at which components are collected from products rejected for remanufacturing	Reje rate for reman	The amount of products rejected for remanufacturing per unit time
Reman rate	The amount of products remanufactured per unit time	Dispos rate	The amount of products disposed of controllably per unit time

Table D3: Auxiliary Variables

Variable	Definition	Variable	Definition
Comp prod capacity	The amount of components that the supplier can produce per unit time	Comp prodn time	The time taken by the supplier in producing a single component
CI cover time	Describes a level of extra stock that is maintained to mitigate risks of stock out. The number of weeks the supplier could ship at the current rate, given its current inventory.	Desired CI	The desired component inventory level
CI discrep	The difference between the desired component inventory level and the current inventory level	Expected distributor's orders	The forecast of distributor's orders by the manufacturer
SI cover time	The number of weeks the supplier could ship at the current rate given its inventory.	Desired SI	the desired inventory level at the supplier
SI discrep	The difference between the desired inventory level and the current inventory level at the supplier	Comp per prod	The number of components in one product
Prdct prdn time	The time taken by the manufacturer to produce one product	SI inv adj time	The time taken by the supplier to correct inventory discrepancies due to changes on demand
Shipment time	The time taken by the distributor to ship product to the retailer	Delivery time	The time taken by the retailer to deliver products to the consumer
Expe retail orders	The forecast of retail orders by the distributor	Expe demand	The forecast of customer demand by the retailer
demand	The actual customer demand for products	Prdct prdn capacity	The amount of prdcts that the manufacturer can produce per unit time
Expe reman prdcts	The forecast of remanufactured products by the manufacturer	Used products	Products collected from the customer at the end of their use
Product life cycle time	The time from when a product is made up to the point when its technology is considered obsolete	Refur lead time	The time from when a product is sold until it is ready

			for sale after reprocessing
Expe reusable comp	The forecast of reusable components	Remanu %	The proportion of collected products that can be remanufactured
Reprocess time	The time taken to remanufacture products	Reman capacity	The amount of products that the company can remanufacture per unit time.
Direct reuse %	The proportion of components from products rejected for remanufacturing that can be reused directly	Residence time	The time that a product dwells with the consumer before being returned to the supply chain.

Appendix E: Model Equations

This appendix lists the equations used in formalising the simulation model. Each stock is listed with both its inflows and outflows.

STOCKS

1. **Collected products**

$$Collected\ products(t) = collected\ products(t - dt) + (total\ collection\ rate - reuse\ acce\ rate - reuse\ reje\ rate) \times dt$$

Initial collected products = 0

Inflows

$$total\ collection\ rate = MIN(company's collection\ capacity, available\ used\ products + products\ not\ collected)$$

Outflows

$$acce\ rate\ for\ prod\ reuse = collected\ products \times \frac{reuse\ \%}{reuse\ inspe\ time}$$

$$reje\ rate\ for\ prod\ reuse = (1 - reuse\ \%) \times \frac{collected\ products}{reuse\ insp\ time}$$

2. **Components inventory**

$$Components\ inventory\ (t) = components\ inventory\ (t - dt) + (comp\ prdn\ rate + comp\ reman\ rate + comp\ acce\ rate\ for\ dir\ reuse - comp\ used\ for\ prdn) \times dt$$

$$Initial\ components\ inventory = 0$$

Inflows

$$comp\ prdn\ rate = MAX\left(MIN\left(MIN\left(\frac{raw\ mat\ inventory}{comp\ prod\ time}, \left(expe\ distributor\ orders \times comp\ per\ product - expe\ reusable\ compo + \frac{CI\ discrep}{CI\ adj\ time}\right)\right), comp\ prod\ capacity\right), 0\right)$$

$$comp\ reman\ rate = MIN\left(comp\ reman\ capacity, \frac{(1 - disposal\ \%) \times comp\ reje\ for\ dir\ reuse}{reproce\ time}\right)$$

$$compo\ acceptance\ rate\ for\ dir\ reuse = \frac{dir\ reuse\ \% \times inv\ of\ comp\ from\ reje\ prdcts}{insp\ and\ disasse\ time}$$

Outflows

$$comp\ used\ for\ prdn = MAX\left(MIN\left(MIN\left(\frac{compo\ inventory}{prdct\ prdn\ time}, prdn\ capacity \times comp\ per\ prdt\right), \left(expe\ dist\ orders - \right.\right.\right.$$

$expe\ reman\ prdcts + \frac{SI\ discrep}{SI\ adj\ time}\Big) \times$
$comp\ per\ prdt\Big), 0\Big)$

3. Components rejected for direct reuse

$comp\ reje\ for\ dir\ reuse\ (t) =$
$comp\ reje\ for\ dir\ reuse\ (t - dt) +$
$(comp\ repla\ rate +$
$comp\ reje\ rate\ for\ dir\ reuse - recycle\ rate -$
$coomp\ reman\ rate - disposal\ rate) \times dt$

$initial\ comp\ reje\ for\ dir\ reuse = 0$

Inflows

$comp\ repla\ rate = reman\ rate \times$
$comp\ per\ prdct \times comp\ repla\ \%$

$$comp\ reje\ rate\ for\ dir\ reuse = \frac{(1 - dir\ reuse\ \%) \times inv\ of\ comp\ from\ reje\ prdcts}{insp\ and\ disasse\ time}$$

$$comp\ reje\ rate\ for\ dir\ reuse = \frac{(1 - dir\ reuse\ \%) \times inv\ of\ comp\ from\ reje\ prdcts}{insp\ and\ disasse\ time}$$

Outflows

$$recycling\ rate = \frac{comp\ reje\ for\ dir\ reuse}{reproce\ time}$$

$$comp\ reman\ rate = \frac{(1 - disposal\ \%) \times comp\ reje\ for\ dir\ reuse}{reproce\ time}$$

$disposal\ rate = comp\ reje\ for\ dire\ reuse \times$
$disposal\ \%$

4. Controllable disposal

$controllable\ disposal\ (t) =$
$controllable\ disposal\ (t - dt) +$
$(disposal\ rate) \times dt$

$initial\ controllable\ disposal = 0$

Inflows

$disposal\ rate = comp\ reje\ for\ dir\ reuse \times$
$disp\ \%$

5. Distributor orders backlog

$distributor\ orders\ backlog\ (t) =$
$distributor\ orders\ backlog\ (t - dt) +$
$(distributor\ orders -$
$distributor\ \ backlog\ red\ rate) \times dt$

$initial\ distributor\ orders\ backlog = 0$

Inflows

$$distributors\ orders = expe\ wholesale\ orders + \frac{DI\ discrepancy}{DI\ adj\ time}$$

Outflows

$distributors\ backlog\ red\ rate =$
$shipments\ to\ distributor$

6. Distributor inventory

$distributor\ inventory\ (t) =$
$distributor\ inventory\ (t - dt) +$
$(shipments\ to\ distributor -$
$shipments\ to\ wholesaler) \times dt$

$initial\ distributor\ inventory = 0$

Inflows

$shipments\ to\ distributor =$

$$\frac{(IF(serviceable\ inventory - distributors\ orders\ backlog \geq 0)THEN(distributors\ orders\ backlog)ELSE(serviceable\ inventory))}{distr\ shipment\ time}$$

Outflows

$shipments\ to\ wholesaler =$

$$\frac{(IF(distributor\ inventory - wholesale\ orders\ backlog \geq 0)THEN(wholesale\ orders\ backlog)ELSE(distributor\ inventory))}{wholesale\ shipment\ time}$$

7. Inventory of components from rejected products

$inv\ of\ comp\ from\ reje\ prdcts\ (t) =$
$inv\_of\_comp\_from\_reje\_prdcts(t - dt) +$
$(comp\_from\_reje\_prodcts -$
$comp\_reje\_rate\_for\_dir\_reuse -$
$compo\_acce\_rate\_for\_direct\_reuse) \times dt$

$initial\ inventory\ of\ comp\ from\ rejected\ products =$
0

Inflows

$comp\ from\ reje\ products =$
$reje\_rate\_for\_reman \times$
$components\_per\_product$

Outflows

$comp\ reje\ rate\ for\ dir\ reuse =$

$$\frac{(1 - direct\_reuse\_\%) \times inv\_of\_comp\_from\_reje\_prdcts}{inspe\ and\ dissasse\ time}$$

$compo\ acce\ for\ dire\ reuse =$

$$\frac{(direct\_reuse\_\% \times inv\_of\_comp\_from\_reje\_prdcts)}{insp\ and\ dissasse\ time}$$

8. Products for remanufacturing

$products\ for\ remn\ (t) =$
$products\ for\ reman\ (t - dt) +$
$(acce\ rate\ for\ reman - reman\ rate -$
$produscts\ cot\ remanufactured) \times dt$

$initial\ products\ for\ reman = 0$

Inflows

$$acce\ rate\ for\ reman = \frac{reje\ prod\ for\ reuse \times reman\ \%}{initial\ inspe\ time}$$

Outflows

$reman\ rate =$
$IF\left(\frac{products\ for\ reman + reman\ backlogs}{reprocess\ time} \geq\right.$
$\left. reman\ capacity\right) THEN (reman\ capacity) ELSE (0)$

$products\ not\ remanufactured =$
$MAX\left(\left(\frac{products\ for\ reman}{reprocess\ time}\right) - reman\ capacity, 0\right)$

9. Products for cannibalisation

$prod\ for\ cannibalisation\ (t) =$
$prod\ for\ cannibalisation\ (t - dt) +$
$(reje\ rate\ for\ reman) \times dt$

$initial\ products\ for\ cannibalisation = 0$

Inflows

$reje\ rate\ for\ reman =$
$\frac{(1 - reman\ \%) \times reje\ prod\ for\ reuse}{initial\ inspe\ time}$

10. Raw material inventory

$raw\ mat\ inventory\ (t) =$
$raw\ mat\ inventory\ (t - dt) +$
$(recycling\ rate - comp\ prod\ rate) \times dt$

$initial\ raw\ mat\ inventory =$
$1000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000$

Inflows

$recycling\ rate = \frac{comp\ reje\ for\ dir\ reuse}{reproce\ time}$

Outflows

$comp\ prdn\ rate =$
$MAX\left(MIN\left(MIN\left(\frac{raw\ mat\ inventory}{comp\ prod\ time}, \left((expe\ distri\ orders \times\right.\right.\right.\right.$
$comp\ per\ prdct) - expe\ reusable\ compo +$
$\left.\left.\left.\left.\frac{CI\ discrepe}{CI\ adj\ time}\right)\right), comp\ prod\ capacity\right), 0\right)$

11. Rejected products for reuse

$reje\ prod\ for\ reuse\ (t) =$
$reje\ prod\ for\ reuse\ (t - dt) +$
$(reje\ rate\ for\ prod\ reuse -$
$acce\ rate\ for\ reman - reje\ rate\ for\ reman) \times$
dt

$initial\ reje\ prod\ for\ reuse = 0$

Inflows

$reje\ rate\ for\ prod\ reuse =$
$\frac{(1 - reuse\ \%) \times collected\ products}{reuse\ insp\ time}$

Outflows

$acce\ rate\ for\ reman = \frac{reje\ prod\ for\ reuse \times reman\ \%}{initial\ inspe\ time}$

$reje\ rate\ for\ reman = \frac{(1 - reman\ \%) \times reje\ prod\ for\ reuse}{initial\ inspe\ time}$

12. Remanufacturing backlogs

$remanufacturing\ backlogs\ (t) = remanufacturing\ backlogs\ (t - dt) + (products\ not\ remanufactured) \times dt$

$initial\ remanufacturing\ backlogs = 0$

Inflows

$products\ not\ remanufactured = MAX\left(\left(\left(\frac{products\ for\ reman}{reprocess\ time}\right) - reman\ capacity\right), 0\right)$

13. Retailer orders backlog

$retailer'sorder\ backlog\ (t) = retailer\ orders\ backlog\ (t - dt) + (retailer'sorders - retailer\ backlog\ red\ rate) \times dt$

$initial\ retailer\ orders\ backlog = 0$

Inflows

$retailer'sorders = expected\ demand + \left(\frac{RI\ discrepency}{RI\ adj\ time}\right)$

Outflows

$retailer\ backlog\ redu\ rate = shipments\ to\ retailer$

14. Retailer inventory

$retailer\ inventory\ (t) = retailer\ inventory\ (t - dt) + (shipments\ to\ retailer - retail\ sale) \times dt$

$initial\ retailer\ inventory = 0$

Inflows

$shipments\ to\ retailer = \frac{(IF(wholesaler\ inventory - retailer\ orders\ backlog \geq 0)THEN(retailer\ orders\ backlog)ELSE(wholesaler\ inventory))}{delivery\ time}$

Outflows

$retail\ sale = IF\left(\left(\frac{retailer\ inventory}{retail\ delivery\ time}\right) \geq 0\right) THEN(demand)ELSE\left(\frac{retailer\ inventory}{retailer\ delivery\ time}\right)$

15. Serviceable inventory

$serviceable\ inventory(t) = serviceable\ inventory\ (t - dt) +$

$(production\ rate + reman\ rate +$
$acce\ prod\ for\ reuse -$
$shipments\ to\ distributor) \times dt$

$initial\ serviceable\ inventory = 0$

Inflows

$production\ rate = \frac{comp\ used\ for\ prdn}{components\ per\ product}$

$reman\ rate =$
$IF\left(\left(\frac{prod\ for\ reman + reman\ backlogs}{reprocess\ time}\right) \geq \right.$
$\left. reman\ capacity\right) THEN (reman\ capacity) ELSE (0)$

$acce\ rate\ for\ reuse = \frac{collected\ products \times reuse\ \%}{reuse\ inspe\ time}$

Outflows

$shipments\ to\ distributor =$
$\frac{((serviceable\ inventory - distributor\ orders\ backlog) \geq 0) THEN (distributor\ orders\ backlog) ELSE (serviceable\ inventory))}{distributor\ shipment\ time}$

16. Wholesaler inventory

$wholesaler\ inventory(t) =$
$wholesaler\ inventory\ (t - dt) +$
$(shipments\ to\ wholesaler -$
$shipments\ to\ retailer) \times dt$

$initial\ wholesaler\ inventory = 0$

Inflows

$shipments\ to\ wholesaler =$
$\frac{IF((distributor\ inventory - wholesaler\ orders\ backlog) \geq 0) THEN (wholesaler\ orders\ backlog) ELSE (distributor\ inventory)}{wholesaler\ shipment\ time}$

Outflows

$shipments\ to\ retailer =$
$\frac{IF((wholesaler\ inventory - retailer\ orders\ backlog) \geq 0) THEN (retailer\ orders\ backlog) ELSE (wholesaler\ inventory)}{delivery\ time}$

17. Wholesaler orders backlog

$wholesaler\ orders\ backlog\ (t) =$
$wholesaler\ orders\ backlog\ (t - dt) +$
$(wholesaler\ orders -$
$wholesaler\ backlog\ redu\ rate) \times dt$

$initial\ wholesaler\ orders\ backlog = 0$

Inflows

$wholesaler\ orders =$
$expected\ retailer\ orders + \left(\frac{WI\ discrepancy}{WI\ adj\ time}\right)$

Outflows

$wholesaler\ backlog\ redu\ rate =$
$shipments\ to\ wholesaler$

AUXILLIARY VARIABLES

$aDI = 2 \times DI\ adjustment\ time$

$aRI = 2 \times RI\ adjustment\ time$

$as\ usual\ demand = LogNormal(4000{,}2000)$

$available\ used\ products =$
$DELAY(retail\ sale, residence\ time)$

$aWI = 2 \times WI\ adjustment\ time$

$CI\ adjustment\ time = 2$

$CI\ cover\ time = 1.5$

$CI\ discrepency = MAX\big((desired\ CI -$
$components\ inventory), 0\big)$

$company'scollection\ capacity = 6000$

$components\ per\ product = 15$

$component\ production\ capacity = (4000 \times 15)$

$component\ production\ time = \frac{1}{(4000 \times 15)}$

$component\ remanufacturing\ capacity =$
(6000×15)

$comp\ replace\ \% = 20$

$delivery\ time = 1$

$demand = as\ usual\ demand$

$desired\ CI = expected\ distributors\ orders \times$
$components\ per\ product \times CI\ cover\ time$

$desired\ DI = expected\ wholesaler\ orders \times$
$DI\ cover\ time$

$desired\ RI = expected\ demand \times$
$RI\ cover\ time$

$desired\ SI = expected\ mdistributors\ orders \times$
$SI\ cover\ time$

$desired\ WI = expected\ retailer\ orders \times$
$WI\ cover\ time$

$direct\ reuse\ \% = 0$

$disposal\ \% = 0.01$

$distributor\ shipment\ time = 1$

$DI\ cover\ time = 1.5$

$DI\ discrepancy = MAX\big((desired\ DI -$
$distributor\ inventory), 0\big)$

$DI\ adjustment\ time = 2$

$expected\ demand = SMTH1(demand, 1)$

$expected\ distributor\ orders =$
$SMTH1(distributor\ orders, aDI)$

$expected\ retailer\ orders =$
$SMTH1(retailer\ orders, aRI)$

$expected\ wholesaler\ orders =$
$SMTH1(wholesaler\ orders, aWI)$

$expected\ reman\ products = SMTH1(reman\ rate, 1)$

$expected\ reusable\ components = SMTH1(compo\ acce\ for\ dir\ reuse + comp\ reman\ rate, 1)$

$initial\ inspection\ time = 1$

$inspection\ and\ dissassembly\ time = 2$

$production\ capacity = 4000$

$products\ not\ collected = MIN\big((available\ used\ products - collection\ capacity), 0\big)$

$product\ production\ time = \frac{1}{4000}$

$remanufacturing\ capacity = 6000$

$remanufacturing\ \% = 0.75$

$reprocess\ time = 1$

$residence\ time = 16$

$reuse\ \% = 0$

$reuse\ inspection\ time = 0.001$

$RI\ cover\ time = 1.5$

$RI\ discrepency = MAX\big((desired\ RI - retailer\ inventory), 0\big)$

$RIadjustment\ time = 2$

$SI\ cover\ time = 1.5$

$SI\ discrepancy = MAX\big((desired\ SI - serviceable\ inventory), 0\big)$

$SI\ adjustment\ time = 2$

$WI\ cover\ time = 1.5$

$WI\ adjustment\ time = 2$

$WI\ discrepancy = MAX\big((desired\ WI - wholesaler\ inventory), 0\big)$

$wholesaler\ shipment\ time = 1$