MODELING ENVIRONMENTALLY RESPONSIBLE SUPPLY CHAINS

by

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Author's Declaration

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Abstract

Modeling Environmentally Responsible Supply Chains, Doctor of Philosophy (2016)

Ehab A. Bazan, Mechanical and Industrial Engineering, Ryerson University

Numerous literature reviews and research studies have highlighted the increasing environmental concerns of supply chain stakeholders (managers, legislative bodies, customers, etc.). Guaranteeing environmentally conscious supply chain operations is closely linked to an organization's sustainability and success. A large part of this is the responsible management of product return flows in production and inventory environments. Reverse logistics is inevitable in today's business environment with the most common reasons being product returns, incorrect product delivery, damaged products, and product exchange programs. Green concepts and should be operationalized in a supply chain context. The literature emphasizes that the modelling of reverse logistics and closed-loop supply chains from a green and/or environmental aspect lacks investigation and development. Mathematical modelling of such systems will assist decision-making processes and provided a better understanding of environmentally responsible inventory models.

This thesis reviews the literature on the modelling of reverse logistics inventory systems that are based on the economic order/production quantity (EOQ/EPQ) and the joint economic lot size (JELS) settings so as to systematically analyse the mathematics involved in capturing the main characteristics of related processes. The literature is surveyed and classified according to the specific issues faced and modelling assumptions. Special attention is given to environmental issues. There are indications of the need for the mathematics of reverse logistics models to follow current trends in 'greening' inventory and supply-chain models. The modelling of waste disposal, greenhouse-gas emissions and energy consumption during production is considered as the most pressing priority for the future of inventory models. Mathematical models for two-level supply chains with different coordination policies, a manufacturing-remanufacturing inventory model and a two-level closed-loop supply chain model with remanufacturing under different coordination are developed in this thesis. Numerical examples are presented and discussed presenting managerial insights and implications. Input-Output system analysis and multi-objective optimization modeling are suggested future research directions.

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Dedication

To Reem Abdelaal, my one and only Pumpkin.

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Chapter 1

INTRODUCTION

This chapter introduces the main concepts and provides a basis for understanding supply chain management and the role of environmental awareness in a supply chain context. Elements of this chapter have been taken from Bazan et al. (2015a) and an accepted book chapter ("The Development and Analysis of Environmentally Responsible Supply Chain Models") in the upcoming editorial book "Green Supply Chain Management for Sustainable Business Practice".

1.1 Introduction

Inventory modeling in supply chains is a prime concern for research in production and operations management and industrial engineering. The approach is to have mathematical representations of systems that can be studied and optimized to satisfy dynamic market demands. Most of these inventory models are managed by the classical analysis (profit-maximization/cost-minimization) approach. There has been a push for businesses and organizations to be accountable and responsible for environmental and social impacts of their operations. This drive has been derived from various internal and external stakeholders leading to new regulations being imposed. Such responsibilities have accounted for the introduction and application of various concepts, programs, and efforts (Richards, 1997). Some of these include: environmental management systems, integrated management systems, corporate social responsibility, life cycle assessment, design for environment, pollution prevention, sustainable development, environmental indicators and reporting to name a few.

Applying environmental management concepts to supply chains is becoming known as green supply chain management. Relatively, this concept is considered in its infancy and many individual efforts using a variety of approaches and methodologies are existent throughout the literature. In light of the current environmental responsibilities, interest in industrial environmental performance metrics is increasing. The coupling of such measures and their integration into product procurement/purchasing decisions, investment decisions, and their effect on supply chain environmental performance will only increase environmental awareness and the ability of decision makers to reach balanced judgments and achieve sustainable choices.

This chapter introduces the importance of environmental awareness in firms and organizations, and the integration of environmental consciousness into supply chains as a necessity for sustainability and continuous improvement.

1.2 Supply Chain and Supply Chain Management

Supply chains are an important element of any business whether it is manufacturing products or providing a service. It is a direct result of differences and discrepancies between supply and demand throughout the different stages of a business. Assume the following scenario of a vendor who supplies products to a buyer: if the demand is more than what the supplier offers, shortages will occur and may lead to possible back-logs or lost sales. Conversely, if the supply available is more than the buyer's demand, excess inventory may incur additional costs. Expanding, there may be more than two parties involved: e.g. many suppliers, multiple products, numerous warehouses, various distributors, etc. The more parties in a supply chain, the more complex it is and the need for careful management is more evident. For a successful supply chain, it should be efficient and responsive. Furthermore, storage and material handling costs in supply chains can be as high as 50% of a product's indirect operating expenses (Rosenblatt, 1986). Consequently, reducing inventory related costs in a supply chain is a priority. The following will provide readers with some of the concepts and definitions.

Supply chains have been defined as "the alignment of firms that bring products or services to market" (Lambert et al., 1998), or as a chain that "consists of all stages involved, directly or indirectly, in fulfilling a customer request. The supply chain not only includes the manufacturer and suppliers, but also transporters, warehouses, retailers, and customers themselves . . ." (Chopra et al., 2003). It has also been defined as “a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers." (Ganeshan and Harrison, 1995). Though slightly different, all definitions share a network, active participants in this network, and a goal to bring a service or product to the end customer. It is not uncommon that participants have conflicting objectives, where each participant would like to maximize (minimize) its profit (cost). Accordingly, supply chain management becomes the means to manage these networks.

Mentzer et al. (2001) defines supply chain management as: “the systematic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purpose of improving the long-term performance of the individual companies and the supply chain as a whole.” From this definition, any participant within a supply chain must make individual and collective decisions concerning five functional areas: production, inventory, facility location, transportation, and information. For example, if the business strategy is to compete on the basis of price, the decisions made must optimize the supply chain for minimum cost. However, if the business strategy is to compete on customer service, the decisions must optimize for responsiveness. Examples of the decisions to be made could be what products to be produced, the quantities of each product produced and delivery times, how much inventory to be stored at each stage, the amount to be held as raw-materials, semi-finished, or finished goods, and/or the optimal inventory level and re-order points. Further questions include the location of production and inventory storage facilities, the means of transportation, what data should be collected, the information to be shared and to what degree of accuracy and timeliness. Essentially, supply chain data synchronization, collaborative planning, forecasting, and replenishment become a necessity for success.

Optimizing a supply chain is the coordination of the decisions along the five functional areas. These coordination policies can be categorized as centralized or decentralized. Decentralized policies involve numerous decisions by each participant within the chain. This often leads to conflict of interest or conflict of individual objectives. However, centralized policies allow a single decision-maker (a team) to manage the supply chain as a whole to achieve an overall objective that is optimal for all participants within the supply chain. Centralized coordination is discussed extensively throughout the literature including various quantitative models. The bulk of this literature considers the economic order quantity model as the base foundation, and the main objective is to optimize the supply chain's combined costs or maximize the overall profit (Jaber and Zolfaghari, 2008; Glock, 2012). Typically when modeling supply chains, the associated costs considered are inventory holding costs, lost sales or shortage costs, order costs and possibly production setup costs if the vendor is a manufacturer.

Equally important to determining the optimal parameters that run the supply chain is the ability to measure its performance. Dr. Peter Drucker's (a notable management consultant) famous quote "what gets measured, gets managed" is often emphasized (Prusak, 2010). Resources, output and flexibility are three types of performance measure that can be used in measuring a supply chain's performance (Beamon, 1999). Generally, there are four measurement categories: customer service, internal efficiency, demand flexibility, and product development (Hugos, 2006). Furthermore, the Supply Chain Council's SCOR model suggests that a system be developed to present data at three levels of details: strategic, tactical (performance metrics), and operational (diagnostic metrics).

As evident, the complexities and depth of each topic in supply chains requires extensive research and investigation. Most of these topics have been economically driven, however there have been recent initiatives to look into both environmental and social aspects.

1.3 Supply Chain Coordination

Supply chain coordination decision-making can be either centralized or decentralized. Decentralized decisions aim at coordinating various decisions by each participant within the chain leading to conflict of individual objectives. For example, shipping a large batch size from a vendor to a retailer may be more economical for the vendor, but incur excessive holding costs for the retailer who may prefer shipments of smaller size. On the other hand, a centralized decision allows a single decision-maker, usually consisting of a team, to manage the chain as a whole to achieve the overall objective that is collectively optimal for all the entities within the chain. An extensive discussion on centralized coordination from an economic order quantity (EOQ) and joint economic lot size (JELS) setting is found in the literature (Glock, 2012; Jaber and Zolfaghari, 2008). Further discussion can be found in the review presented in Cachon (2003); however, the focus of this paper is restricted to EOQ and JELS settings, which is the basis of the developed model. Different coordination decisions in a supply chain may improve the overall performance depending on specific circumstances. The vendor-managed inventory (VMI) with consignment stock (CS) agreement (VMI-CS), modelled by Braglia and Zavanella (2003) in a two-level (vendor–buyer) supply chain, has been shown to be advantageous over the classical coordination of Hill (1999), for different situations (Bazan et al., 2014; Jaber et al., 2014a]. The concept of VMI-CS is having inventory stored at the buyer, but managed by the vendor (Braglia and Zavanella, 2003). Holweg et al. (2005) showed that VMI and CS are mistakenly taken for being the same. In a VMI system the replenishment of orders for the buyer is determined by the vendor, where in a CS system the replenishment order is determined by the buyer (CS merely refers to items stored at the buyer's facility owned by the vendor).

1.4 Environmental Awareness in Supply Chains

According to a joint initiative by the Supply Chain and Logistics Association Canada, and the Retail Council of Canada (2009) in their report on green supply chain management, they state that green supply chain management is the incorporation of environmental thinking into supply chain management. They further state that this "includes introducing technical and innovative processes into materials sourcing and selection, delivery of the final product to consumers, and end-of-life product management." The wished-for result is the improvement of an organization's environmental impact while increasing its efficiency and progress within its supply chain. Examples of green supply chain management practices include (but are not limited to): energy efficiency, reduction of greenhouse gas emissions, water conservation or processing, waste reduction, reduced packaging or increased use of biodegradable packaging, product and packaging recycling, and green procurement practices. The above list can also be used to illustrate environmental benefits stemming from green supply chain management principles. Furthermore, the report also lists business benefits that can be achieved including: distribution efficiency, compliance, distribution cost, customer retention, and differentiate services.

Implementing green supply chain management is not without challenges and pitfalls. To maximize the benefits from productive green supply chain management practices, organizations should align their business targets with their environmental ones, tailor their own roadmaps or implementation plans and make the benefits from such an alignment clear to their supply chain partners. Moreover, an important aspect is the development of clear and appropriate metrics that are universally understood to measure performance.

Generally, the literature classifies green supply chain management into three main categories: the importance of green supply chain management, green design, and green operations (Srivastava, 2007). Green design is fundamentally based on either life cycle analysis/assessment (LCA) or on an environmental conscious design (ECD). Green operations, as presented in the review by Srivastava (2007), is of three main subcategories: green manufacturing and remanufacturing, reverse logistics and network design, and waste management. Srivastava (2007) further illustrates a timeline of the literature exhibited under each of the categories. However, what is seen to be a necessity is the overlapping of these interdisciplinary topics from these subcategories to produce more effective research agendas resulting in applicable and relevant benefits academically and, more important, practically via the industry.

These classical models evaluate a supply chain's economic performance and do not capture environmental awareness, which is mainly the result of societal and governmental pressures. Today, it is necessary to incorporate environmental thinking into supply chain management (Bonney and Jaber, 2011). That is, there are environmental costs associated with activities performed in a supply chain. These costs affect the performance of a supply chain and therefore can no longer be ignored (Bonney and Jaber, 2011). Greening supply chain activities also has benefits (Ferretti et al., 2007; Jaber and Goyal, 2008). This entails saving of depleting resources, cutting down consumption of energy which have become increasingly costly, reducing waste and pollution, and marketing a ‘‘green-image’’. Regardless of the reasoning behind the adoption of this approach by an organization, the wished-for result is ultimately the improvement of the organization's environmental impact, yet remaining efficient and effective from a business standpoint.

Environmental efforts in supply chain modelling based on EOQ and JELS settings are, generally, geared towards the reduction of greenhouse gas (GHG) emissions as presented in the literature review (see Chapter 2). This may be misleading by perceiving that the highest priority of environmental concerns is the reduction of GHG emissions. Industrial production will always yield an undesirable environmental impact of which GHG emissions are a part of, but contrary to this perception, a large component of this impact is from energy consumption (Devoldere et al., 2007). Countries with considerable industrial production, Germany for example, have industries consuming 27% of energy production with 47% of that being electrical energy (Dietmair and Verl, 2009). The manufacturing sector in the United States of America accounts for roughly 33% of the energy consumption and emits roughly 28% of greenhouse gas emissions (Mouzon and Yildirim, 2008). In Turkey, the industrial sector accounts for about 35% of the total energy consumed and about 52% of total electricity used (Önüt and Soner, 2007). Recently, significant efforts have been made in EU to improve the energy efficiency, for instance, the recently adopted Energy Efficiency Directive (EED) set targets for energy efficiency, including the obligation on Member States to achieve a certain amount of final energy savings over the obligation period 01-January-2014 to 31-December-2020 (European Commission, 2012). Generally, efforts are being made to minimize the consumption of energy, and these efforts are increasing as a result of price and demand increases for petroleum and other fossil fuels coupled with the depletion of energy commodities and concern for global warming (Mouzon and Yildirim, 2008). Research concerning product recovery shows that there is a hierarchy for recovery of products (Carter and Ellram, 1998; El Saadany, 2009; Guide Jr. and Van Wassenhove, 2009; Steven, 2004; Souza, 2013) where the first option for recovery is always to reduce the consumption of required resources: material, fuel, energy, etc… (see Figure 1.1). This reinforces the previous discussion where the reduction of energy consumption is of significant importance. Furthermore, reducing resource consumption will also directly lead to a reduction in GHG emissions as considerable amounts of energy are produced from non-renewable sources, which contributes to the GHG emitted to the atmosphere (Mouzon et al., 2007). Accordingly, it becomes a priority to equally consider energy consumption with GHG emissions in the context of supply chains and their modelling, which is the focus of this paper.

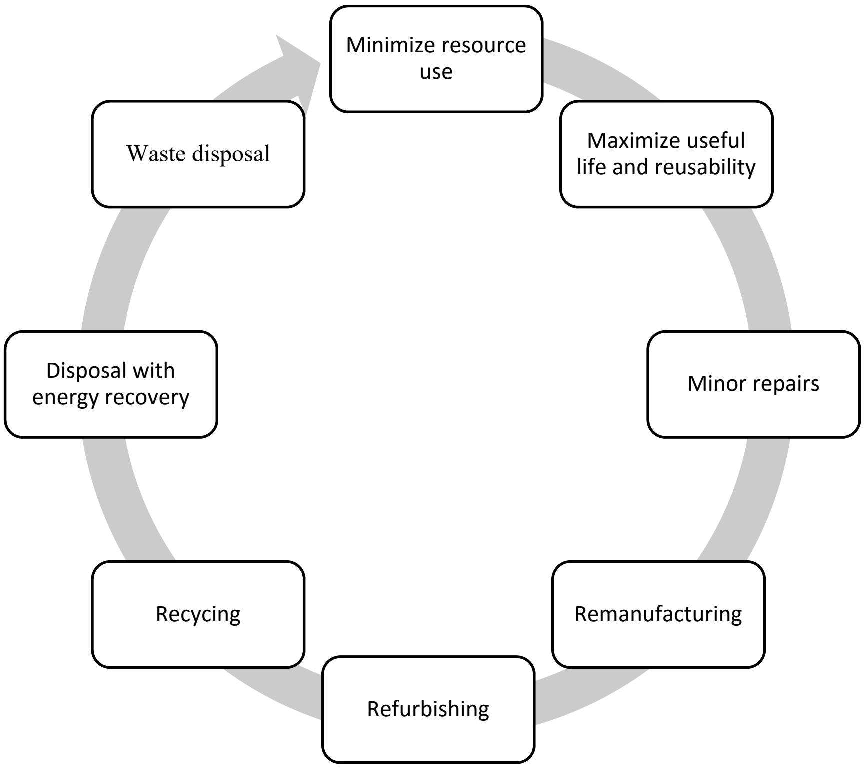

Figure 1.1 *General hierarchy of recovery operations*

1.5 Reverse Logistics: A First Step

There are numerous definitions presented for reverse logistics. Some of these define reverse logistics in a similar fashion to that of a traditional (forward) supply chain. If a traditional supply chain is one that involves raw material acquisition, manufacturing, and distribution of products to the customer, then reverse logistics is the reverse flow of products from the customer that involves the collection, inspection, disassembly, and distribution of used products to the point where recycling, remanufacturing, repair and recovery is possible with the purpose of recapturing value or appropriate disposal (Rogers and Tibben-Lembke, 1999; Dowlatshahi, 2000; Bei and Linyan, 2005).

Reverse logistics is not a newly introduced concept. The economic benefits of reusing products and materials have been previously applied (Fleischmann et al. 1997). Moreover, environmental concerns and newly introduced legislations have added motivation to the existing economic benefits leading to increase in the development of reverse logistics activities (Fleischmann, 2001). Some of these environmental concerns include scarce availability of landfill sites, declining raw material and energy resources, damages to the ozone, etc. These environmental concerns coupled with the environmental legislations allowed businesses and organization to extend developments in increasing product life, the ability to recycle more of the products and even reduce greenhouse-gas (GHG) emissions to the air (Bei and Linyan, 2005; Gülsün et al, 2006; Bonney and Jaber, 2011).

Van Hoek (1999) looks into reverse logistics as a research point that can be expanded to other research areas in green supply chain management. The perspective is to understand the impacts of some business practices on the environment and the entire supply chain. The focus of this study was to look at challenges of research on green supply chain management to lower the "ecological footprint" of supply chains. Of their findings was a categorization of green approaches in the supply chain research field. The impact of upstream and downstream integration of green practices along the supply chain is explored by Vachon and Klassen (2006). Reverse-logistics mathematical models such as El Saadany and Jaber (2010) do consider disposal and remanufacturing. Utilizing reverse logistics to manage returned products coincides with the goals of being environmentally responsible by reducing or minimizing environmental impacts. Reverse logistics and green supply chains overlap and have shared commonalities as explored by Marsillac (2008). Marsillac (2008) emphasises these shared processes and aims and concludes by suggesting that the integration of green supply chains and reverse logistics into a comprehensive system will improve and contribute beyond the individual successes of each separately. The dissimilarity between green supply chains and reverse logistics, it that the first focuses on the economic benefits stemming from the recovery activities whereas the latter shares these with environmental benefits (De Brito and Dekker, 2003; Bei and Linyan, 2005).

In a nutshell, reverse logistics can be considered a sub-set of closed-loop supply chains which in turn are a sub-set of green supply chains which are part of a more encompassing supply chain referred to as a sustainable supply chain. This is depicted in Figure 1.2.

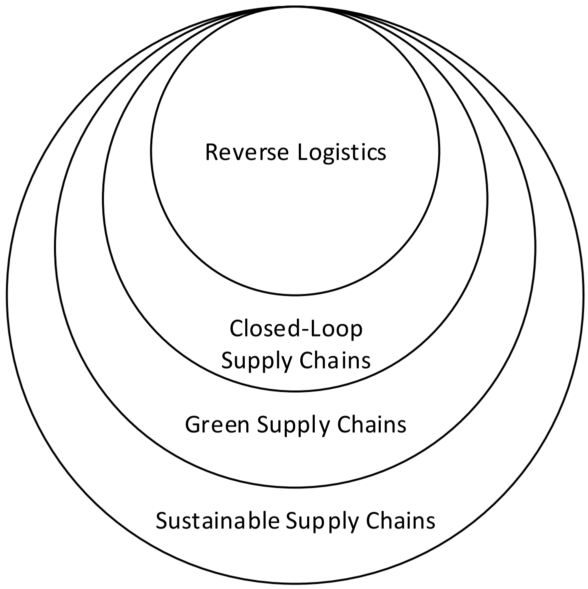

Figure 1.2 *Reverse logistics, closed-loop, green and sustainable supply chains*

More on green supply chains shall be discussed in the upcoming literature review section. What is important is that there is growing concern regarding the management of product return flows. These growing concerns stem from both economic and environmental motives. Inventory models for reverse logistics should be extended to encompass both these economic and environmental aspects. The literature shows that there is plenty of expansion possible in this area.

The importance of modeling supply chain models that are environmentally responsible is an issue that requires immediate attention. Natural resources are finite and the impact of current industry supply chains are detrimental to the environment. This chapter summarized the current efforts in the inventory modeling of 'green' supply chain and shows a growing need for supply chain models to expand beyond modeling GHG emissions. It is evident that in order to achieve progress towards a more sustainable operation both researchers and practitioners alike need to collaborate and tackle all three phases of environmentally responsible supply chains: system analysis, performance metrics, and finally valid mathematical modeling of supply chains.

Chapter 2

LITERATURE REVIEW

This chapter provides a comprehensive literature review pertaining to environmentally responsible and green supply chains and their modeling with special focus given to reverse logistics. Given their importance as the stepping stone to green supply chains, the mathematical modeling of reverse logistics that are based on EOQ and JELS are reviewed and presented. Elements of this chapter have been taken from Bazan et al. (2015a), an accepted book chapter ("The Development and Analysis of Environmentally Responsible Supply Chain Models") in the upcoming editorial book "Green Supply Chain Management for Sustainable Business Practice", and Bazan et al. (2015c).

2.1 Green Supply Chain Models

The literature shows an effective supply chain is essential for the success of firms and organizations; however, as stakeholders become more environmentally responsible, the same responsibility is beginning to translate into supply chain management policies.

Lamming and Hampson (1996) investigate the issues present for purchasing and supply chain managers from an environmental perspective. They mention that, traditionally, environmental issues have not been a priority for supply chain decision makers. Their study suggests that supply chain management practices such as vendor assessment, total quality management, lean supply and collaborative supply strategies can benefit from life-cycle analysis, waste management and other environmental management approaches.

Inman (1999) review the impacts and effects on production planning and inventory control from both an academic and industrial perspective. It is evident that environmental concerns have more of an impact on business operations and represent a challenge to be addressed efficiently and effectively. Inman (1999) explores these implications with a focus on the areas of production planning, inventory control, and product distribution.

Angell and Klassen (1999) utilize a focus group of environmental and operations management researches to generate a framework that helps identify opportunities for integrating environmental issues into the field of operations management. The objective of Walton et al. (1998) is to identify supply chain "environmentally-friendly practices" (EFP). Two topics become apparent: the significance of management's commitment to apply supply chain EFP, and the need to be more proactive rather than just comply with environmental regulations. As a result, supply chain management is evolving and to support this evolution, tools such as life cycle assessment (LCA) are integrated into supply chains (Hagelaar and van der Vorst, 2002). Darnall et al. (2008) examine whether business adopting environmental management systems would be more likely to utilize green supply chain management practices. Their results suggest that both complement each other and that the organizations that have an environmental management system in place are more likely to practice green supply chain management practices and have a higher probability of improving the environment.

Zhu and Sarkis (2004) investigate the relationship between green supply chain management practices and environmental and economic performance. They conclude that the application of green supply chain management practices was more likely to create win-win situations with regards to both environmental and economic performance of the enterprise. Furthermore, they show that the enterprises investigated who have an existing quality management program in place, along with the green practices, demonstrated superior performance. Extending their previous work, Zhu and Sarkis (2006) use an empirical study to investigate the relationship between green supply chain management operational practices and performance amongst early adopters in China. Other empirical studies are performed by Holt and Ghobadian (2009) in the United Kingdom where they indicate they most pressure is on manufacturers to implement green practices, by Jabbour and Jabbour (2009) where their focus was on green practices in supplier selection, and by Thun et al. (2010) for the automobile industry in Germany where they show implementation of green supply chain management yields higher performance. This conclusion also coincides with the results presented from another empirical research performed by Green Jr et al. (2012).

Seuring and Muller (2008) look into stimulating further research in the field by offering a literature review on sustainable supply chain management from 1994 to 2007. They present a conceptual framework to summarize the research in this field and deduce two strategies for research moving forward: supplier management and risk performance, and supply chain management for sustainable products. They highlight that the research is dominated by green and environmental issues, and that the social issues studied are few and occasional. A "state-of-the-art" literature review was performed by Srivastava (2007) to identify major research work and provide a clear classification of green supply chain management. The purpose of the review was to classify the literature to identify research gaps, issues and potential areas for future research. Srivastava (2007) concludes that green supply chain management can reduce the ecological consequences of business activities without sacrificing performance, quality, reliability, or cost. Other literature reviews were performed by Luthra et al. (2009) to discuss green supply chain management issues, by Ilgin and Gupta (2010) where the review was more focused on issues pertaining to environmentally conscious manufacturing and product recovery, and by Mollenkopf et al. (2010) to investigate research and industry practice regarding simultaneous implementation of green, lean, and global supply chain strategies. Further categorization of green supply chain management and future research directions are presented in the review by Sarkis et al. (2011).

Sustainability is a multidisciplinary topic that has gathered momentum and most recently within economic, business and management fields (Linton et al., 2007). Linton et al. (2007) provide a background review to help understand the current concepts and trends of sustainability in operations management and to present the research opportunities and challenges associated with it. They show how supply chains and sustainability fuse together. As a result, the focus on environmental management and operations is shifted from a more local perspective to a more comprehensive one covering the entire supply chain. They suggest that "supply chains must be explicitly extended to include by-products of the supply chain, to consider the entire lifecycle of the product, and to optimize the product not only from a current cost standpoint but also a total cost standpoint." They further discuss that the total cost must reflect the effects of depleting resources, pollutants, wastes, etc. Linton et al. (2007) conclude that research into the implications of these concerns on the operations and supply chain is a binding necessity. Similar works concerning research challenges for sustainability are presented in the work of Garetti and Taisch (2012).

Examining the importance of inventory planning to the environment in detail is the focus of Bonney and Jaber (2011). They highlight the value of designing inventory systems that echo the needs of the environment and coin this term "responsible inventory systems". Notable in their research are the environmental inventory performance metrics suggested and the extension of a simple economic order quantity (EOQ) model to an "environmental-EOQ" model to account for the "true" cost of an activity, one that includes the environmental costs. True costs in a classical supply chain may be difficult to calculate (Jaber, 2009) which highlights that environmental costs may be of a more daunting task.

Clearly, several research frameworks have been presented, however the need to operationalize these concepts remain open for exploration. Table 2.1 lists research papers in chronological order and classifies the literature into (marked by "X"): (1) qualitative, (2) quantitative, (3) conceptual framework, (4) surveys, (5) case studies, (6) reviews, (7) research agendas, and (8) performance measures.

Table 2.1 *Summary of the select literature reviewed pertaining to the issues of the environment and supply chain management*

Research Article	Qualitative	Quantitative	Conceptual Framework	Modeling	Focus-Groups and/or Surveys	Case Study	Literature Review	Research Opportunities	Performance Measures
Lamming and Hampson (1996)	X		X		X		X	X	
McIntyre et al. (1998)		X	X			X		X	X
Walton et al. (1998)	X				X	X			

Research Article	Qualitative	Quantitative	Conceptual Framework	Modeling	Focus-Groups and/or Surveys	Case Study	Literature Review	Research Opportunities	Performance Measures
Angell and Klassen (1999)	X		X		X		X	X	
Beamon (1999)	X		X				X		X
Inman (1999)	X						X	X	
van Hoek (1999)	X		X					X	
Sarkis (2003)			X	X			X	X	
Zhu and Sarkis (2004)		X		X	X	X			X
Hervani et al. (2005)			X		X	X			X
Kainuma and Tawara (2006)		X		X		X			X
Vachon and Klassen (2006)		X			X				
Zhu and Sarkis (2006)		X			X				
Kumar (2007)		X		X					X
Linton et al. (2007)							X		
Srivastava (2007)							X	X	
Darnall et al. (2008)	X		X		X		X		
Marsillac (2008)	X		X				X	X	
Seuring and Müller (2008)							X	X	
Zhu et al. (2008)		X			X	X			X
Holt and Ghobadian (2009)		X	X		X				
Jabbour and Jabbour (2009)	X					X			
Luthra et al. (2009)		X	X	X					
Thun et al. (2010)		X	X		X				
Benjaafar et al. (2010)		X		X			X		
Chaabane et al. (2010)		X		X					

Research Article	Qualitative	Quantitative	Conceptual Framework	Modeling	Focus-Groups and/or Surveys	Case Study	Literature Review	Research Opportunities	Performance Measures
El Saadany and Jaber (2010)		X		X					
Ilgin and Gupta (2010)	X						X		
Mollenkopf et al. (2010)		X	X						
Bonney and Jaber (2011)	X		X				X	X	
Bonney and Jaber (2013)	X		X				X	X	
El Saadany et al. (2011)		X	X	X				X	X
Faruk et al. (2011)	X		X		X	X			
Garetti and Taisch (2011)			X				X		
Hua et al. (2011)		X		X					
Sarkis et al. (2011)		X							
Wahab et al. (2011)		X		X					
Battini et al. (2012)		X		X					
Green Jr et al. (2012)		X		X	X				
Jaber et al. (2013)		X		X					
Soysal et al. (2014)		X		X					
Brandenburg et al. (2014)	X						X	X	
Govindan et al. (2015)	X						X	X	
Rezaee et al. (2015)		X		X					
Agrawal et al. (2015)	X						X	X	

Earlier works (from 1996 to 2003) listed in Table 2.1 focused on conceptual ideas and designs and suggested frameworks for future research opportunities. Later papers (from 2004 onwards) tried to quantify the concepts and frameworks develop in earlier works and introduce performance metrics to help assess and evaluate the environmental performance of supply chains. These studies were mainly based on case studies and focus groups. Subsequently, from 2009 onwards there have been considerable efforts to quantify the environmental performance of a supply chain, but these studies focused, only, on measuring carbon emissions (carbon footprints) and energy consumption. Research works considering a more holistic view of the supply chain and its environmental issues are more qualitative in nature and mathematically modeling their behavior remains a challenge.

2.2 Modeling of Green Supply Chains

The necessity for incorporating environmental thinking into supply chain management is presented in Bonney and Jaber (2011). Numerous environmental problems stem from the production and transportation of goods across a supply chain. Greenhouse-gas (carbon) emissions due to transportation and manufacturing processes, other air emissions, fuel consumed for transportation, depletion of natural resources and raw material, energy consumed for manufacturing, scrapping (solid waste) and biodegradability of products and packaging, water usage, chemical and toxic/hazardous waste, thermal pollution and noise. The world's resources are finite, whether it be material for manufacturing, or fuel or energy sources, or even clean air and a pristine ozone layer. The risk of having unsustainable practices along a supply chain can hinder the environment tremendously. The question remains, can inventory be planned to help mitigate and even better, help the environment. Storage locations, shipped batch sizes, the number of orders and the means of transportation are some questions that supply chains can be addressed when modeling supply chains and can have considerable impact on the environment. With the intention of operating supply chains to protect and sustain the environment performance measures need be introduced that consider the inter-relationships between inventory and the environment. Generally, the environmental performance measures should push towards environmentally-sound activities and stray away decisions that are harmful to the environment (Bonney and Jaber, 2011). For example, activities such as reuse or remanufacturing are more desirable than recycling as less energy is involved and less waste generated.

The amalgamation of environmental interests into the organizational and inter-organizational practices of a supply chain including that of reverse logistics is how Sarkis et al. (2011) define green supply chain management. There are over twenty other definitions for green supply chain management as presented in Ahi and Searcy (2013). It is clear from Ahi and Searcy (2013) that there are overlaps in the definitions provided, but the common theme is the integration of the environmental concerns into the supply chain activities and processes with the purpose of saving resources and reducing both emissions and wastes. It is clear that green supply chain management is a requirement for a more comprehensive sustainable supply chain management approach. The 'greening' of activities have several benefits including saving natural resources, lowering energy costs, and avoiding unnecessary waste and pollution (Zhu and Sarkis, 2004; Ferretti et al., 2007).

An environmental decision making tool was constructed by McIntyre et al. (1998) for the integrated supply chain at Xerox Ltd. They show how they provide a measure of environmental performance for the whole supply chain as well as for the individual functional elements within the chain. Preliminary results of their work show that the working-life of a product is what causes the biggest environmental impact. Of significant importance in their research is the "environmental common denominator" approach that has been implemented. They assume that all processes or functions have three main environmental issues, namely: the amount of energy consumed, the materials used, and the pollutants emitted, that comprise the environmental common denominators. The integrated supply chain presented consists of the following seven functions: acquire, assemble, distribute, install, working-life, remove, and asset-recovery. In their opinion, their decision tool helps in devising a practical approach to achieve a win-win scenario where the "right-product" can be delivered to the "right-customer" at the "right-time" whilst minimizing the associated environmental impacts.

According to Beamon (1999), the traditional structure of supply chains ought to be extended to include mechanisms for product recovery and new associated performance measures. This work discusses and investigates the environmental factors leading to the development of an extended environmental (green) supply chain. Beamon (1999) develops a general procedure towards achieving and maintaining a green supply chain.

Faruk et al. (2001) develop a management tool for analyzing, mapping, and managing environmental impacts along supply chains. In their research, Faruk et al. (2001) assess environmental impacts as either "guidance hierarchies" or "categories of emission stress". The guidance hierarchies are classified as: ecosystem disturbance, material types, energy sources, solid waste, shipping distance, and mode of transport. The categories of emission stress relate to emissions of air and water only and are classified into two classes where class I consists of global climate change, ozone depletion, and toxicity to water, and class 2 consists of acidification, nutrification, and photochemical smog formation. Faruk et al. (2001) consider the following stages: material acquisition, preproduction, production, use, distribution, and disposal. In the assessment matrix presented the guidance hierarchies and categories of emission stress are listed against these stages with regards to material inputs, energy use, solid waste, liquid emissions, atmospheric emissions, and intersite contexts.

Sarkis (2003) presents a decision framework to aid in managerial analysis and decision making in the area of green supply chain management. It suggests structuring and modeling the elements of a supply chain network and applying an analytical network process to the problem. The advantage of the technique presented is the ability to provide decision makers with the flexibility to identify and integrate the inter-dependencies present in a supply chain network, while considering the network's environmental and economic characteristics.

Hervani et al. (2005) integrate research in supply chain management, environmental management and performance management into a single framework that allows for evaluation and review based on the following categories: inputs, outputs, controls and tools. They present a list of selected metrics and measures of environmental performance. Each of which has strategic, tactical and operational managerial implications. Even though the indicators are many, the predicament remains in which to use, how to measure it, and when to measure it.

Kainuma and Tawara (2006) propose a multi attribute utility theory method to assess supply chains that they consider to be a "lean and green supply chain" method. The objective is to extend the supply chain to include reuse and recycling throughout the life cycle of products and services in the chain.

Energy or fuel consumed due to transport and storage, carbon-dioxide emissions due to transport and storage, and financial cost of operating a supply chain (excluding the production steps) are three metrics used by Kumar (2007) when presenting a model to analyse a two-level supply chain. Kumar (2007) uses this model and studies the energy usage, emissions and cost for various industries. In general, the model shows opportunities for improving energy and emissions footprints of supply chains.

Zhu et al. (2008) looks into how to evaluate green supply chain management practices and their implementation amongst manufacturers in the Chinese industry. Their study was performed through an empirical investigation where the data collected is tested against two measurement models for green supply chain management. The first list of measurable factors includes internal environmental management, green purchasing, cooperation with customers, eco-design and investment recovery each of which may have several measurement items. The second list of measurement items is for performance outcomes; namely environmental and economic performance, again each of which is measured with several measures.

Benjaafar et al. (2010) use a simple model to illustrate how carbon emissions could be integrated into procurement, production and inventory management operational decisions. Their approach is to modify a traditional model to support decision making by associating carbon emissions parameters with the various decision variables. The main use of the model is to show the extent where carbon emissions can be reduced by addressing operational adjustments. Also focusing on carbon management strategies under the carbon emission trading mechanism is the works of Chaabane et al. (2012) and Hua et al. (2011). Fixed and variable emission costs are considered in a two-level supply chain model presented by Wahab et al. (2011). Jaber et al. (2013) also consider a two-level supply chain and present a model that jointly minimise the costs related to inventory and green-house-gas emissions costs when penalties for exceeding emissions limits are considered. They consider different emissions trading schemes.

Bonney and Jaber (2013) present an input-output activity matrix (IOAM) to analyze manufacturing and logistics systems and its performance. This IOAM illustrated in their work shows how each tier of a logistics chain may be analyzed to improve both its economic and environmental performance. Bonney and Jaber (2013) suggest that using the IOAM linking the economic and environmental aspects of a system can be a successful analysis. What they propose is a framework that has not yet been operationalized.

El Saadany et al. (2011) consider a coordinated two-level supply chain and seek to fill a gap in the literature by modeling the supply chain and developing an analytical decision model that can explore the performance when product, process, and environmental quality features are considered. Results show that investing to reduce environmental costs will improve environmental performance and increase profits. In the work of El Saadany et al. (2011) is a list of numerous quality environmental measures of a supply chain that are categorized under the following: product-based elements, manufacturing-based elements, product working life, operations-based elements, and finally green image and perceived quality.

Battini et al. (2014) explore the integration of economic and environmental objectives within a traditional EOQ model and propose a sustainable EOQ model. The approach requires a complete analysis from the beginning of the purchase order to the end of the product life at the buyer's facility. To identify all these environmental impacts arising during the life time of the purchase order a life cycle assessment (LCA) approach is applied. Essentially, Battini et al. (2014) consider the environmental inputs to be materials and energy, and the outputs to be air, water and solid emissions at each stage of the life cycle for the purchase order. They compute these inputs and outputs in order to apply them to the EOQ theory relating to transportation costs and external costs.

Principally, there are three thoughts raised. First, the notion that the majority of literature has been qualitative in nature, but nevertheless, present important concepts in implementing green supply chain management and suggesting future research streams. There are exceptions where quantitative research is shown but these are restricted to inventory models incorporating carbon emissions and/or energy consumption. Second, there is research that highlights the progression of reverse logistics to green supply chain management. However, again the mathematical models present for reverse logistics do not encompass all environmental factors associated with the impacts. Third, with the establishing of environmental performance measures there are several works where frameworks have been suggested to analyze supply chain systems, but such frameworks have not been operationalized. Furthermore, performance measures presented in the literature have not been applied in a supply chain context.

2.3 Inventory Models Based on EOQ and JELS Dealing with Environmental Issues

Studies that deal with environmental issues in inventory systems are progressively increasing in number. Examining the importance of inventory planning to the environment in detail was the focus of Bonney and Jaber (2011). They highlighted the value of designing inventory systems that echo the needs of the environment termed ‘‘responsible inventory systems’’. Notable in their research are the environmental inventory performance metrics they suggested and the extension of a simple EOQ model (Harris, 1913) to an ‘‘environmental-EOQ’’ model to account for the ‘‘true’’ cost of an activity, one that includes the environmental costs, mainly GHG emissions. Following the work of Bonney and Jaber (2011), several papers along the same line of research started appearing in the literature, mainly presenting mathematical models that describe different supply chain settings. The focus of these studies was integrating the cost of GHG emissions into the supply chain total cost function. A brief review of these works is provided next.

The following works are based on the JELS problem (Banerjee, 1986; Goyal, 1988), which has been the foundation for the classical supply chain centralised coordination models in the literature (Glock, 2012; Jaber and Zolfaghari, 2008). Wahab et al. (2011) considered several models of a two-level supply chain with fixed and variable emissions costs with a local or an overseas unreliable supplier, who ships lots that contain non-conforming items. Their modelling was based on that EOQ model of Salameh and Jaber (2000). They assumed that GHG emissions are generated from transporting goods. El Saadany et al. (2011) presented a two-level supply chain model where demand at the buyer's side is price and quality dependent, which are decision variables, and quality is an aggregated measure (0 to 1) including environmental quality such as air pollution and solid waste in addition to energy usage. Hua et al. (2011) and Chaabane et al. (2012) focused on carbon management strategies under the carbon emissions trading mechanism. The first derived an EOQ model for a firm in a supply chain, while the second presented a different and complex modelling approach to evaluate trade-offs between economic and environmental objectives in the aluminium industry. Glock et al. (2012) showed how inventory in a supply chain is affected when demand is dependent on price and quality of a product. They used product quality index (0 to 1) as a measure of sustainability of the levels of scrap, associated with an investment function, and GHG emissions. Their demand function is of a simpler form than that of El Saadany et al. (2011). Jaber et al. (2013) also considered a two-level supply chain and presented a model intended to jointly minimize inventory and GHG emissions costs when penalties for exceeding emissions limits were considered. Unlike earlier works, which restricted GHG emissions to transporting inventory, Glock et al. (2012) and Jaber et al. (2013) associated emissions to the production process. Jaber et al. (2013) considered an emissions trading scheme, while Glock et al. (2012) did not. Recently, Zanoni et al. (2014a) investigated the model of Jaber et al. (2013) with VMI-CS and their results showed that VMI-CS resulted in lower total costs and lower GHG emissions levels. Finally, Benjaafar et al. (2013) used a simple model to illustrate how carbon emissions could be integrated into procurement, production and inventory management operational decisions. They used their model to show the extent to which carbon emissions can be reduced through operational adjustments. These surveyed models are based on the EOQ model. Although it has been critiqued by some (Jaber, 2009; Jaber et al., 2004), it continues to be celebrated in the academic literature. Readers may refer to Choi (2014), Glock et al. (2014), and Andriolo et al. (2014) for reviews on EOQ and JELS. Glock et al. (2014) did not touch on environmental issues, while the others did.

Manufacturing and associated processes consume enormous amounts of energy along with other resources, and consequently have a huge impact on the environment (Vijayaraghavan and Dornfeld, 2010). Initial environmental studies for machine tools show that the majority of the machine tools' environmental impact is a result of electrical consumption and that the reduction of electrical energy demands is crucial (Li et al., 2011). Measures are required to be taken to reduce energy costs and increase efficiency, especially with the current uncertainty in energy costs (Önüt and Soner, 2007). Generally, total production costs include raw material cost, labour cost, maintenance cost, operational cost, etc.; with energy cost is just a portion of operational cost. Managers tend to give it little consideration (Önüt and Soner, 2007). It can be further argued that the focus of machine designers is mainly on the effective working life of the machine and little attention is given to minimizing the energy consumption (Devoldere et al., 2007).

The overall environmental performance of manufacturing systems can be significantly improved through the reduction of energy consumption of machine tools (Vijayaraghavan and Dornfeld, 2010; Li et al., 2011). One of the first steps to achieve a reduction in energy consumption of machine tools is to find ways to measure and determine their energy consumption (Vijayaraghavan and Dornfeld, 2010). In the literature, there is some work regarding the cost of energy in production (e.g. Dietmar and Verl, 2009; Mouzon and Yilidrim, 2008; Mouzon et al., 2007), while other works showed how energy usage can be related to a machine's production rate (Gutowski et al., 2006) or to the scheduling of a steel plant (Nolde and Morari, 2010). These works considered a single-stage system. Other research accounted for energy usage in a two-stage production system with variable production rates (Zanoni et al., 2014b). Another approach to estimating the energy usage in materials production and manufacturing was to develop a life-cycle energy analysis tool (Gutowski et al, 2011).

Even though the focus of this literature is restricted to models based on the EOQ and JELS settings, there are other research works regarding environmental issues in supply chains that employ other approaches. For example, Hoen et al. (2014), Demir et al. (2014), and Lin et al. (2014) studied green transportation, and Jain et al. (2013) and Xie (2015) focused on energy. In addition, other works that may be referred to are concerning supplier selection (Genovese et al., 2013; Lu et al., 2007), integrated modelling approaches (Mirzapour et al., 2013; Sundarakani et al., 2010), and/or empirical case studies (Glover et al., 2014; Lee, 2011). These works are beyond the scope of this paper, but are listed to increase the reader's awareness.

The literature pertaining to EOQ and JELS settings, for the most part, discusses important concepts in implementing green supply chain management and suggesting future research streams. Quantitative research is available, but these works are generally restricted to inventory models incorporating carbon emissions as presented above. Several research frameworks have been suggested to incorporate other environmental issues (see Bonney and Jaber (2011) for details) asides just GHG emissions, but the need to operationalize these concepts remains open for exploration, and furthermore, they have not yet been applied in EOQ and JELS models (Bonney and Jaber, 2013; Bonney and Jaber, 2014). This remains to be an interesting and promising research venue to be pursued in a future work. Concluding, the literature presented shows that environmental concerns are being integrated into the approaches to designing, coordinating and operating supply chains. The surveyed works focused on GHG emissions; however, the studies presented show that energy and energy-related costs affect inventory and production decisions, which implies that one can no longer ignore these costs.

2.4 Classification of Reverse Logistics Inventory Models

The concept of reverse logistics is not new. The reuse of products, components, and materials has been previously applied, mainly for the economic benefits of reusing the product or material instead of its disposal (Fleischmann et al., 1997). In addition to economic motivations, environmental concerns have directed the increase in the development of reverse logistics activities. Moreover, government pressure and legislation have contributed to the increasing motivation for global environmental awareness and sustainability influencing green supply chain management principles and practices (Sheu and Chen, 2012). One such approach is the Extended

Product Responsibility (EPR) legislation, which concentrates on the life-cycle and environmental performance of products (Subramanian et al., 2009) and fundamentally holds producers physically and financially responsible for the environmental impact of their products after their life has reached an end (Atasu and van Wassenhove, 2012). Concerns regarding declining landfill sites, depletion of resources and damage to the ozone layer, along with environmental legislation have led to the developments required for prolonging product life, recycling, and reducing greenhouse-gas (GHG) emissions (Bei and Linyan, (2005); Gülsün et al., (2006); Bonney and Jaber, 2011).

Quantitative inventory models and closed-loop supply chains can be classified under three main categories: distribution planning, inventory control, and production planning (Fleischmann et al., 1997). The focus of this paper is solely on the mathematical modelling of the inventory models with return flows that are based on EOQ and JELS settings. The general objective of the inventory management models is to control product orders, inventory levels, and recovery processes to guarantee a specific service level and minimize total costs associated. A first model was presented by Schrady in 1967 (Fleischmann et al., 1997). This paper provides a review of the studies that provided mathematical models that cite and extend the work of Schrady (1967) up to August 2014. The research papers are classified based on content related issues and modelling assumptions.

Inventory models are classified as either (a) single or multi-echelon, (b) deterministic or stochastic, and (c) one-for-one or batch repair and replenishment (Guide and Srivastava, 1997). There are different solution tools and techniques (single and multi-objective linear, integer, non-linear and mixed-integer programming…) that can be used to solve the various content related issues, including inventory models, reverse distribution and product recovery activities (Sasikumar and Kannan, 2009). Reverse logistic networks can be organized as: directly reusable, remanufacturing, repair service, and recycling networks (Bostel et al., 2005]). This classification basically depends on the type of product considered. Recovery activities are distinguished as product, component, material, and energy recovery activities (De Brito and Dekker, 2003). The demand and return processes presented in the literature could be dependent, independent of each other, or dependent on price and quality, and are assumed as a continuous constant rate, a continuous dynamic rate, an arbitrary function of time, or not explicitly modelled (De Brito and Dekker, 2003; Singh and

Saxena, 2012). Further, the demand and return rates could be assumed deterministic where all model parameters are known throughout the planning horizon, or stochastic which takes into account the uncertainty. Another important characteristic of 'return flow' inventory systems is the number of stock points and the type of stock inventory (Akçalı and Cetinkaya, 2011). These stock points can be classified as manufactured items, remanufactured items, combined manufactured and remanufactured items, new material items, and used item inventory (Akçalı and Cetinkaya, 2011). From this classification it is clear that the quality of the remanufactured items is either assumed as-good-as-new or different from the newly produced. The management of quality for different items has also been investigated in the literature (El Saadany and Jaber, 2010). In general, a typical remanufacturing environment can be distinguished by the motivation behind the product recovery, the type of item to be recovered, the form of recovery, the activities required for recovery, the agents performing the recovery process, and finally the location of the recovery activities (Akçalı and Cetinkaya, 2011). Repair shops can either be in-house or independent, and if spare parts are considered, they can be ordered from the original equipment manufacturer (OEM) or they can be repaired (Kleber et al., 2011).

Using the various classification and categorization from the aforementioned literature, the research papers regarding the modelling of inventory management of reverse logistics can be identified under the following categories and sub-categories:

- Type of Model
    - EOQ, optimal, optimal quadratic, simulation, linear programming, integer programming, mixed integer programming
    - Single objective, multi-objective
    - Deterministic, stochastic
    - Number of decision variables
    - Decision variable (batch quantity, production rate, number of batches, …)
- Inventory Stock
    - Number of stock points (single-stock, two-stock, three-stock, and multi-stock points)
    - Types of stock points (new/raw material, manufactured item, used item,

remanufactured item, manufactured and remanufactured item inventories)

- Recovery Process
  - Recovery activities (collection, inspection, separation, and disassembly)
  - Form of recovery
    - Product recovery (repair, refurbishment, reuse, remanufacturing, and repair)
    - Material recovery (recycling)
    - Component recovery (remanufacturing)
    - Energy recovery
    - Location of recovery activity (existing and/or separate facilities)
- Modelling Assumptions
  - Demand rate (not considering, constant, price sensitive, arbitrary function of time)
  - Production rate (not considering, constant, demand-dependant, arbitrary function of time)
  - Return rate (not considering, constant, demand-dependant, price and quality dependant, arbitrary function of time)
  - Remanufacturing/repair rate (not considering, constant, demand-dependant, arbitrary function of time)
  - Quality of the remanufactured items (as-good-as-new, different from newly produced)
  - Shortages (allowed/not-allowed)
  - Used item repair and replenishment (one-for-one repair and replenishment, batch repair and replenishment)
  - Number of times allowed to recycle
  - Number of times allowed to reuse
  - Single/multi-item products
  - Spare parts/components (purchased new from OEM, repaired)
  - Product/component obsolescence
- Environmental Factors
  - Greenhouse-gas (carbon) emissions
  - Other air emissions

- Energy consumption/use
- Scrapping (solid waste)
- Biodegradability
- Noise
- Chemical waste
- Water usage
- Toxic/hazardous waste
- Fuel consumption
- Thermal pollution

Concluding, there is sufficient research on reviewing reverse logistic models, inventory management in reverse logistics; however, a specific review of the mathematics involved in quantitative models that operationalize the reverse logistics concepts has not been provided. This paper seeks to present the evolution of the mathematics and highlight future research trends that should be addressed.

2.5 Quantitative Reverse Logistics Inventory Models

The importance of a repairing and recovering inventory was documented back in the 1960s. Schrady (1967) was the first to address this in a quantitative model. The work of Schrady (1967) can be considered the corner-stone for inventory models that are based on the EOQ and JELS settings in reverse-logistics. The core mathematical modelling extensions, as seen by the authors, are the works of Richter and Teunter and later amalgamated by El Saadany. These works, whether individually or collaborated with other authors, have been selected based on the relevant content proposed in each of their research works. Figure 2.1 summarizes the evolution of research by these authors.

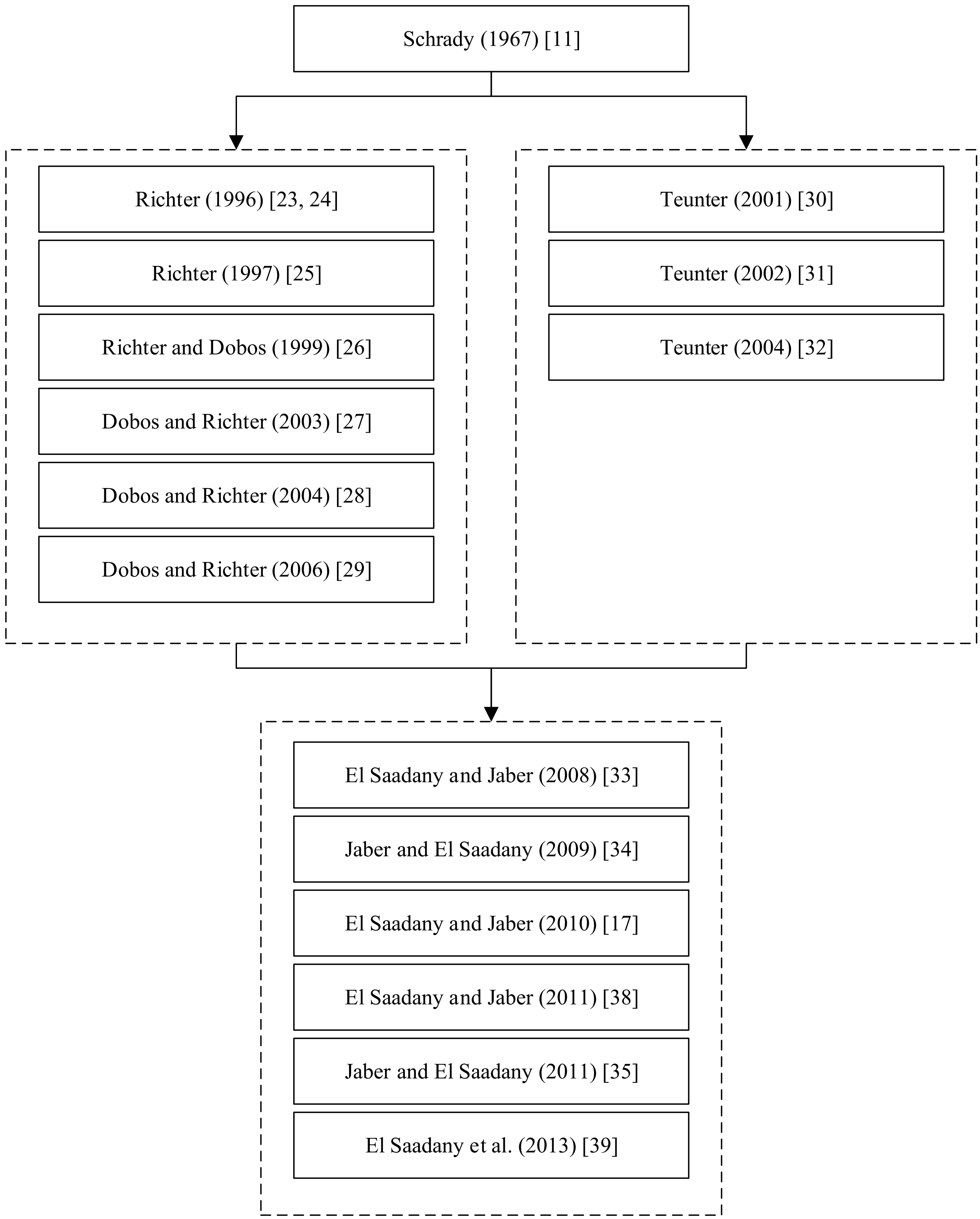

Figure 2.1. *Main inventory models for reverse logistics*

Schrady (1967) proposed an EOQ model considering the repair of items with manufacturing and recovery rates. Richter (1996b, 1996a) assumed that collected items may or may not be recoverable, which is different from the assumption adopted by Schrady (1967) that assumed a continuous flow of used items returning to the manufacturer. This assumption by Richter (1996b, 1996a) implies that some items may be disposed of as waste. Richter (1997) and Richter and Dobos (1999) extended the earlier work of Richter to show that a policy of no waste (i.e., all returned items are to be repaired) or a policy of no repair (i.e., all items are disposed as waste) are optimal compared to a mixed policy. Dobos and Richter (2003) extended the models by assuming a finite production and repair rate. The model is then generalized in Dobos and Richter (2004) for multiple production and repair cycles. In a later paper, Dobos and Richter (2006) considered the quality of the returned items and assumed that not all returned items can be reused. They further showed that a mixed policy of remanufacturing used items and producing new ones is better than a pure policy of no waste or no repair that was suggested by earlier studies.

Similar to Richter, Teunter (2001) extended the work of Schrady (1967). Teunter (2001) assumed that unit holding costs for newly manufactured and remanufactured items are different and considered more than one production and repair cycles. Teunter (2002) considered stochastic demand and return rates and assumed no lead time. Discounted costs were also considered to make the model resemble more realistic situations. Teunter (2004) presented simplified closed form expressions to determine the optimal lot-size quantities for the production or procurement of new items and the collection of used ones for recovery for finite or infinite production and recovery rates.

El Saadany and Jaber (2008) addressed a limitation in the work of Richter (1996b, 1996a), which accounted for accumulating inventory as a result of no repairs (recovery) occurring in the very first time interval of a product’s life. They also extended the model to account for setup changeover costs when switching between production and remanufacturing runs. Jaber and El Saadany (2009) assumed that the quality of returned items is less than the quality of newly manufactured items and hence the demand for newly produced items is different from that for remanufactured items. They further assumed lost sales as a result and consider two cases where the demand for manufactured or remanufactured is lost completely, or where it may be possible to satisfy some demand for new items with remanufactured items at a cost. El Saadany and Jaber (2010) suggested that the return flow of used items from the market is variable and depends on two decision variables: the purchase price and the accepted quality level of the returned items. Quality was assumed as a percentage of useful parts of a used item. The collected returned items are given a cut-off quality percentage if matched or exceeded, the item is considered eligible for remanufacturing or else it is disposed as waste. Tackling the same economic issues for a production and remanufacturing model from a different perspective, Jaber and El Saadany (2011) extended the model of Dobos and Richter (2003, 2004) for learning in production and remanufacturing processes. Learning is more than just worker skill improvement through training or experience from repeating a set task; it involves technological progress and collective efforts of numerous staff members across the process (Jaber (2009). As learning occurs, the amount of time to produce (remanufacture) and to sort, inspect and disassemble a collected used item is reduced and hence learning can be used to better enhance the performance of an inventory and logistics system (Waldman and Yourstone, 2011). El Saadany and Jaber (2011) revisited the existing models by assuming a bill of material for manufactured items that consists of subassemblies and components that are disassembled and individually managed upon return. A common and unrealistic assumption in the models of Schrady, Richter, and Teunter is that items can be repaired an unlimited number of times, which El Saadany et al. (2013) relaxed. A mathematical expression for finite recovery was developed and applied to the models of Richter (1997) and Teunter (2001). They associated the increase in the number of recovery times with capital investment to use environmentally friendly material and to improve product design, e.g.; design for remanufacturing.

Similar research with different assumptions has also been developed by various authors. These works are not shown in Figure 1 as the mathematics involved do not directly follow the streams of either Richter or Teunter's models. Some recent works include Hasanov et al. (2012), Ali et al. (2013), Feng and Viswanathan (2014), Parvini et al. (2014) and Omar and Yeo (2014), amongst others. Jaber et al. (2014) looked at a consignment stock policy when considering production, remanufacturing and waste disposal. Feng et al. (2013) considered perishable items, whereas Singh and Saxena (2013) and Mishra (2012) considered deteriorating items with possible demand shortages. A non-classical approach involving entropy cost is applied by Jaber and Rosen (2008) and later extended by Jaber et al. (2011) with entropy and exergy costs, where exergy costs represent the loss of potential work destroyed because of entropy (disorder) in a system, which happens naturally with time. Such an approach is believed by the authors to be able to account for costs that are usually hidden or difficult to estimate. A brief survey using the 'Google Scholar' search engine showed (as of August 2014) that there are 310 research papers that cite the work of Schrady (1967), of which 183 are mathematical models seeking to understand and operationalize reverse logistic concepts in inventory management (Appendix B). Focusing on the core papers as seen by the authors, the next section will portray and discuss the evolution of the mathematics for the literature presented.

The following section selects specific models from those presented in Figure 1. Schrady (1967) is selected as this model is the beginning of inventory models considering reverse or return flow of products (Fleischmann et al., 1997). Almost 30 years later, Richter (1996a) extended the work of Schrady (1967) with a fundamental change in that the first environmental considerations appear in the modelling. Waste disposal costs are considered giving it an environmental twist in the discussion. Teunter (2001) also generalized the work of Schrady (1967) and differentiated it from Richter (1996a) by considering a variable disposal rate, and that the holding costs for manufactured and remanufactured items are different. Continuing along the lines of the Richter and Teunter clusters, years later again, El Saadany et al. (2013) provided another primary change in the assumptions that has considerable environmental implications. El Saadany et al. (2013) discussed that materials and products can be repaired a number of times before the product either loses characteristics or cannot be physically repaired anymore. This assumption is more realistic and has added a new shift in the modelling. It is an assumption that implies more waste is disposed than has been accounted for in previous models. A brief summary of the mathematics for the selected papers can be found in Appendix A.

A couple of observations could be taken from the mathematical review presented. Noticeable from the papers reviewed in the three clusters is that all models assume a continuous flow of manufactured products sold by the manufacturer directly to the market and a similar continuous flow for returned items to the manufacturer. Realistically, returned items may be collected at locations before being shipped in batches to the repair shop. Moreover, there could be capacity constraints for the storage facilities.

A survey of the 183 papers (some conference papers have been omitted from the survey) shows that none of these models considered environmental effects of the recovery activities considered. A quick search for the word "environmental" appears in 87 documents of the 183. A more specific search shows that the words "carbon emission" and "GHG emissions" do not appear at all. There is one instance for the word "greenhouse", 12 instances for the word "emissions" and 40 for the word "green". The word "fuel" occurred in 6 documents and energy appeared in 24 documents. The majority of the documents mention these environmental keywords, but do not consider them in their modelling. Some only have these keywords appear in their reference and some have them appear in a context that is not relevant to the inventory scope (e.g. part of the product design, or modelling an inventory system in the context of an exergy system). Those that have the environmental consideration in the modelling are limited to either including the environmental factor as part of many components in the unit production cost, or a combined environmental/quality factor. A summary of these results (totalling 55 documents) is presented in Table 2.2. Table B1 in Appendix B shows a complete list of all documents considered in the survey for the convenience of the reader. The documents presented in Table B1 that are not present in Table 2.2 do not have any of the keywords. Note that not all listed documents in Table B1 are in the reference section.

Table 2.2. *Subset of articles citing Schrady (1967) with environmental keywords (KEY: Not rel. = not relevant, Yes, Not mod. = Yes, but not modelled, Yes, mod. = Yes and modelled)*

Article Name (APA format)	**Emissions, 12 documents**	**Greenhouse, 1 document**	**Green, 40 documents**	**Energy, 24 documents**	**Fuel, 6 documents**
Meyer, F. L. (1973). Analysis of the United States Navy Uniform Inventory Control Program and a proposed repair/procurement interface model. NAVAL POSTGRADUATE SCHOOL MONTEREY CALIF.	No	No	No	No	Not rel.
Teunter, R. H. (2001). Economic ordering quantities for recoverable item inventory systems. Naval Research Logistics (NRL), 48(6), 484-495.	No	No	No	Yes, Not mod.	No
Teunter, R. H. (2001). A reverse logistics valuation method for inventory control. International Journal of Production Research, 39(9), 2023-2035.	Yes, Not mod.	No	No	Yes, Not mod.	No
Zhang, Y. (2001). Environmentally conscious supply chain.	Yes, Mod.	No	Yes, Mod.	Yes, Mod.	No
Rubio Lacoba, S. (2003). El sistema de logística inversa en la empresa: análisis y aplicaciones.	No	No	Not rel.	No	No
Sheu, J. B., Chou, Y. H., & Hu, C. C. (2005). An integrated logistics operational model for green-supply chain management. Transportation Research Part E: Logistics and Transportation Review, 41(4), 287-313.	No	No	Yes, Mod.	No	No
Inderfurth*, K., Lindner, G., & Rachaniotis, N. P. (2005). Lot sizing in a	No	No	Yes, Not mod.	No	No

Article Name (APA format)	Emissions, 12 documents	Greenhouse, 1 document	Green, 40 documents	Energy, 24 documents	Fuel, 6 documents
production system with rework and product deterioration. International Journal of Production Research, 43(7), 1355-1374.					
Buscher, U., & Lindner, G. (2007). Optimizing a production system with rework and equal sized batch shipments. Computers & Operations Research, 34(2), 515-535.	No	No	Yes, Not mod.	No	No
Choi, D. W., Hwang, H., & Koh, S. G. (2007). A generalized ordering and recovery policy for reusable items. European Journal of Operational Research, 182(2), 764-774.	No	No	No	Yes, Not mod.	No
Chung, C. J., & Wee, H. M. (2008). Green-component life-cycle value on design and reverse manufacturing in semi-closed supply chain. International Journal of Production Economics, 113(2), 528-545.	Not rel.	No	Yes, Mod.	No	No
Chung, S. L., Wee, H. M., & Yang, P. C. (2008). Optimal policy for a closed-loop supply chain inventory system with remanufacturing. Mathematical and Computer Modelling, 48(5), 867-881.	No	No	No	No	Not rel.
Rubio, S., & Corominas, A. (2008). Optimal manufacturing–remanufacturing policies in a lean production environment. Computers & Industrial Engineering, 55(1), 234-242.	Yes, Not mod.	No	Yes, Not mod.	No	No

Article Name (APA format)	Emissions, 12 documents	Greenhouse, 1 document	Green, 40 documents	Energy, 24 documents	Fuel, 6 documents
Jaber, M. Y., & Rosen, M. A. (2008). The economic order quantity repair and waste disposal model with entropy cost. European Journal of Operational Research, 188(1), 109-120.	No	No	Not rel.	Not rel.	No
Gu, Q. L., & Ji, J. H. (2008). An integrated logistics operational model for Remanufacturing/Manufacturing system based on the consumer market. International Journal of Logistics Systems and Management, 4(1), 21-39.	No	No	Yes, Not mod.	No	No
Bu, X., & Xu, S. (2008, October). The profit model in reverse logistics under the different environment factors. In Service Operations and Logistics, and Informatics, 2008. IEEE/SOLI 2008. IEEE International Conference on (Vol. 1, pp. 1215-1220). IEEE.	No	No	No	Yes, Mod.	No
Chung, C. J., Quaddus, M. O. H. A. M. M. E. D., & Wee, H. M. (2008, July). Optimizing replenishment policy for short-life-cycle product with recovery considering uncertain delivery. In Machine Learning and Cybernetics, 2008 International Conference on (Vol. 7, pp. 3952-3957). IEEE.	Not rel.	No	Yes, Not mod.	No	No
Li, C., Yang, X., & Zhang, Z. (2008, October). An Extended EOQ Model in Production-Recycling System. In Wireless Communications, Networking	No	No	No	No	Not rel.

Article Name (APA format)	Emissions, 12 documents	Greenhouse, 1 document	Green, 40 documents	Energy, 24 documents	Fuel, 6 documents
and Mobile Computing, 2008. WiCOM'08. 4th International Conference on (pp. 1-5). IEEE.					
Fan, W., Ru, Y., Wang, Y., & Yao, C. (2008, October). Stochastic inventory control model with manufacturing and remanufacturing hybrid system. In Service Operations and Logistics, and Informatics, 2008. IEEE/SOLI 2008. IEEE International Conference on (Vol. 1, pp. 1268-1271). IEEE.	No	No	Yes, Not mod.	No	No
Jaber, M. Y., & El Saadany, A. (2009). The production, remanufacture and waste disposal model with lost sales. International Journal of Production Economics, 120(1), 115-124.	No	No	No	No	Not rel.
Wee, H. M., & Chung c, C. J. (2009). Optimising replenishment policy for an integrated production inventory deteriorating model considering green component-value design and remanufacturing. International Journal of Production Research, 47(5), 1343-1368.	Not rel.	No	Yes, Mod.	No	No
Hwang, H., Ko, Y. D., Yune, S. H., & Ko, C. S. (2009). A closed-loop recycling system with a minimum allowed quality level on returned products. International Journal of Services and Operations Management, 5(6), 758-773.	No	No	Not rel.	No	No

Article Name (APA format)	Emissions, 12 documents	Greenhouse, 1 document	Green, 40 documents	Energy, 24 documents	Fuel, 6 documents
El Saadany, A. (2009). Inventory management in reverse logistics with imperfect production, learning, lost sales, subassemblies, and price/quality considerations.	Yes, Not mod.	No	Yes, Not mod.	Yes, Mod.	No
Topcu, A. (2009). A heuristic approach based on golden section simulation-optimization for reconfigurable remanufacturing inventory space planning.	No	No	No	Yes, Not mod.	No
Chang, Y. J., & Yao, M. J. (2009). A genetic algorithm for solving the economic lot scheduling problem with reworks. Journal of the Chinese Institute of Industrial Engineers, 26(5), 411-425.	No	No	Yes, Not mod.	No	No
Lee, Y. J. (2009). Integrated forward-reverse logistics system design: An empirical investigation (Doctoral dissertation, Washington State University).	Not rel.	No	Yes, but not modelled	Not rel.	No
Chung, C. J., & Wee, H. M. (2009). An Integrated production inventory deteriorating model for short life-cycle green product remanufacturing.	No	Yes, Mod.	Yes, Mod.	Yes, Not mod.	No
El Saadany, A., & Jaber, M. Y. (2010). A production/remanufacturing inventory model with price and quality dependant return rate. Computers & Industrial Engineering, 58(3), 352-362.	No	No	Not rel.	Yes, Mod.	No

Article Name (APA format)	Emissions, 12 documents	Greenhouse, 1 document	Green, 40 documents	Energy, 24 documents	Fuel, 6 documents
Sana, S. S., & Chaudhuri, K. (2010). An EMQ model in an imperfect production process. International Journal of Systems Science, 41(6), 635-646.	No	No	No	Yes, Mod.	No
Yuan, K. F., & Gao, Y. (2010). Inventory decision-making models for a closed-loop supply chain system. International Journal of Production Research, 48(20), 6155-6187.	No	No	Not rel.	No	No
Johar, B. O. (2010). Inventory control issues in a disassembly line.	No	No	Yes, Not mod.	Yes, Not mod.	No
Poles, R. (2010). System Dynamics modelling of closed loop supply chain systems for evaluating system improvement strategies (Doctoral dissertation, RMIT University).	No	No	Yes, Not mod.	Yes, Not mod.	Not rel.
Ying, Z., Tijun, F., Hong, Z., & Weixia, X. (2010, August). Economic ordering quantities for manufacturing/recovery inventory system with outsourcing. In Emergency Management and Management Sciences (ICEMMS), 2010 IEEE International Conference on (pp. 130-134). IEEE.	No	No	Yes, Not mod.	No	No
Liu, X. (2010). Hierarchical decision making with supply chain applications (Doctoral dissertation, Drexel University).	No	No	Yes, Not mod.	Yes, Not mod.	No
Chung, C. J., & Wee, H. M. (2011). Short life-cycle deteriorating product	No	No	Yes, Mod.	Yes, Not mod.	No

Article Name (APA format)	Emissions, 12 documents	Greenhouse, 1 document	Green, 40 documents	Energy, 24 documents	Fuel, 6 documents
remanufacturing in a green supply chain inventory control system. International Journal of Production Economics, 129(1), 195-203.					
El Saadany, A. M. A., Jaber, M. Y., & Bonney, M. (2011). Environmental performance measures for supply chains. Management Research Review, 34(11), 1202-1221.	Yes, Mod.	No	Yes, Mod.	Yes, Mod.	No
Alamri, A. A. (2011). Theory and methodology on the global optimal solution to a General Reverse Logistics Inventory Model for deteriorating items and time-varying rates. Computers & Industrial Engineering, 60(2), 236-247.	No	No	No	Yes, Mod.	No
Jaber, M. Y., Saadany, A. M. E., & Rosen, M. A. (2011). Simple price-driven Reverse Logistics system with entropy and exergy costs. International Journal of Exergy, 9(4), 486-502.	Yes, Not mod.	No	Yes, Not mod.	Not rel.	No
Wee, H. M., & Widyadana, G. A. (2012). Economic production quantity models for deteriorating items with rework and stochastic preventive maintenance time. International Journal of Production Research, 50(11), 2940-2952.	No	No	Yes, Not mod.	No	No
Tsai, D. M. (2012). Optimal ordering and production policy for a recoverable item inventory system with learning effect.	No	No	Yes, Not mod.	No	No

Article Name (APA format)	Emissions, 12 documents	Greenhouse, 1 document	Green, 40 documents	Energy, 24 documents	Fuel, 6 documents
International Journal of Systems Science, 43(2), 349-367.					
Plewa, M., & Jodejko-Pietruczuk, A. (2012). THE REVERSE LOGISTICS MODEL WITH REUSING OF COMPONENTS OF SERIES SYSTEM PRODUCT. Reliability: Theory & Applications, 7(1).	No	No	No	No	Yes, Not mod.
Mishra, V. K. (2012). Production Inventory Model for Deteriorating Items with Shortages and Salvage Value Under Reverse Logistics. International Journal of Mathematical Modelling & Computations, 2(2).	No	No	No	Yes, Mod.	No
Singha, S. R., Prasherb, L., & Saxenaa, N. (2013). A centralized reverse channel structure with flexible manufacturing under the stock out situation. International Journal of Industrial Engineering Computations, 4(1).	No	No	Yes, Not mod.	No	No
Wee, H. M., & Widyadana, G. A. (2013). A production model for deteriorating items with stochastic preventive maintenance time and rework process with FIFO rule. Omega, 41(6), 941-954.	No	No	Not rel.	No	No
Andrew-Munot, M., & Ibrahim, R. N. (2013). Development and analysis of mathematical and simulation models of decision-making tools for	No	No	Yes, Not mod.	No	No

Article Name (APA format)	Emissions, 12 documents	Greenhouse, 1 document	Green, 40 documents	Energy, 24 documents	Fuel, 6 documents
remanufacturing. Production Planning & Control, 24(12), 1081-1100.					
Ali, S. S., Madaan, J., Chan, F. T., & Kannan, S. (2013). Inventory management of perishable products: a time decay linked logistic approach. International Journal of Production Research, 51(13), 3864-3879.	Not rel.	No	Yes, Not mod.	No	No
Li, J. (2013, January). Price Decision Analysis for Reusable Product Under Asymmetric Information. In Proceedings of 20th International Conference on Industrial Engineering and Engineering Management (pp. 935-941). Springer Berlin Heidelberg.	No	No	No	Yes, Not mod.	No
Singh, S. R., & Saxena, N. (2013). A Closed Loop Supply Chain System with Flexible Manufacturing and Reverse Logistics Operation under Shortages for Deteriorating Items. Procedia Technology, 10, 330-339.	No	No	Not rel.	No	No
Benkherouf, L., Skouri, K., & Konstantaras, I. (2013). Optimal lot sizing for a production-recovery system with time-varying demand over a finite planning horizon. IMA Journal of Management Mathematics, dpt015.	No	No	Yes, Not mod.	Yes, Not mod.	No
Dem, H., & Prasher, L. (2013). Imperfect Production System under Reverse Logistics in Stock-Out Situation: EPQ	No	No	Yes, Not mod.	No	No

Article Name (APA format)	Emissions, 12 documents	Greenhouse, 1 document	Green, 40 documents	Energy, 24 documents	Fuel, 6 documents
Model. Advances in Decision Sciences, 2013.					
Kim, T., & Glock, C. H. (2014). On the use of RFID in the management of reusable containers in closed-loop supply chains under stochastic container return quantities. Transportation Research Part E: Logistics and Transportation Review, 64, 12-27.	No	No	Not rel.	No	No
Yu, J. C. Pricing strategy for product reuse at three quality levels when demand is sensitive to price and availability.	No	No	Yes, Not mod.	No	No
Flapper, S. D., Gayon, J. P., & Lim, L. L. (2014). On the optimal control of manufacturing and remanufacturing activities with a single shared server. European Journal of Operational Research, 234(1), 86-98.	No	No	Not rel.	No	No
Ahiska, S. S., & Kurtul, E. (2014). Modeling and analysis of a product substitution strategy for a stochastic manufacturing/remanufacturing system. Computers & Industrial Engineering, 72, 1-11.	No	No	Yes, Not mod.	Yes, Not mod.	No
Singh, S. R., Jain, S., & Pareek, S. An economic production model for time dependent demand with rework and multiple production setups.	No	No	Yes, Not mod.	No	No
Jaber, M. Y., Zanoni, S., & Zavanella, L. E. (2014). A consignment stock	No	No	No	Yes, Not mod.	No

Article Name (APA format)	Emissions, 12 documents	Greenhouse, 1 document	Green, 40 documents	Energy, 24 documents	Fuel, 6 documents
coordination scheme for the production, remanufacturing and waste disposal problem. International Journal of Production Research, 52(1), 50-65.					

For the most part, the mathematics focus on determining costs as a function of optimal batch sizes and optimal number of batches. Examples include the ignoring of transportation costs, fuel consumed for transportation and GHG emissions associated, let alone other environmental factors. Assuming capacitated trucks travelling for fixed distances for the transportation of items in the forward and reverse flows it is obvious that the number of trucks is a function of the batch size and number of batches. Consequently, associated transportation costs, fuel consumptions, and GHG emissions can be related to the decision variables which will definitely affect the suggested inventory policy. One could suggest modifying the mathematics to determine system costs not only as a function of batch sizes and number of batches, but possibly production rates or collection rates which may be more reflective on associated environmental factors. Also including quality levels as a decision variable and modifying the mathematics accordingly may lead to significant insights regarding investment costs and higher return rates, a possible decrease in waste and some financial benefits. A quick look at the mathematics easily shows the numerous opportunities for expanding current inventory models of reverse logistics to bear more resemblance of real world logistical networks.

2.6 Reverse Logistics Inventory Models: Take-Away Message

The complexity of the models and the mathematics has evolved with time and with the relaxation of assumptions. The objective of most of the models is to minimize the total cost of the system. The majority of the models do so by optimizing the order quantity or the batch size. However, some studies have different decision variables that include the number of production batches in a cycle, the number of repair/remanufacture batches in a cycle and even price, or the purchase price and the accepted quality levels of returned items. Also based on the assumptions relaxed and/or considered, the inventory stock points and types may vary and the recovery process activities. Based on the classifications and categorizations presented in section 2, the models presented are summarized, highlighting the inventory stock points and recovery activities.

Throughout the three clusters, all models can be classified as single objective, linear models based on the EOQ model, except for El Saadany and Jaber (2011), which is a mixed integer problem, and all are deterministic except for Teunter (2002). Although the paper of Schrady (1967) focuses on searching for procurement and repair batch quantities, the papers in the Teunter cluster focus on the manufacturing batch size, whereas the Richter cluster focus on the production and remanufacturing/recycling lot sizes. The El Saadany cluster, however, focuses on a range of decision variables. All three clusters consider two stock points for used items and a combined stock point for the manufactured and remanufactured items, with the exception being Dobos and Richter (2003, 2004, 2006) where the two stock points considered are used items and manufactured items. The papers of all three clusters consider collection and repair as the recovery activities with Dobos and Richter (2003, 2004, 2006) and the El Saadany cluster adding inspection as well. Jaber and El Saadany (2009) and El Saadany and Jaber (2011) extended the recovery activities to include remanufacturing, with the latter including disassembly as well as a result of considering component recovery as opposed to product recovery as a whole. The aforementioned classifications are presented in Tables C1, C2 and C3 respectively of Appendix C.

In general, the objectives of the various research problems are extensions of the classical EOQ inventory problem and revolve around determining the optimal batch size for production, the optimal batch size for repair/remanufacturing, and the number of production and repair/remanufacturing in a time interval to minimize the total costs of the system. The complexity of the models under the various assumptions discussed in the previous section has kept mathematical models limited to two-inventory stock points: that of the first shop that produces ‘serviceable’ items ready for use, and that of the second shop that accumulates used items ready to be repaired or remanufactured. Further, the recovery activities involve product recovery operations only. It should be noted that the models presented in Table C3 show that the recovery activities include repair or remanufacture recovery activities only, even though they may be described as recycling or remanufacturing in their respective works. The terminology has been corrected for some of these works based on the definitions provided in Glavič and Lukman (2007). For example, the work of Dobos and Richter (2003) uses the term recycling; however, recycling refers to recovering material, but what actually occurs in their model is the repairing of returned used items to a state where it is as-good-as new. Another example is the work of El Saadany and Jaber (2011) where disassembly is part of the process and hence remanufacturing is the correct term used. In addition to the definitions presented in Glavič and Lukman (2007), an in-depth discussion of the various recovery terms and which ones to apply are presented in King et al. (2006).

Essentially, inventory models for reverse logistics are complex and in order to mathematically model and solve for optimal scenarios they have been simplified with numerous assumptions. The evolution of the mathematical models has, for the most part, been driven by two factors: assumptions regarding product demand, demand of returned items and collection rates for returned items, and the quality of the returned items. Even with the presented work, there is immense room for extensions. One can assume similar cost parameters as those presented, but introduce a second product to the system, or an additional tier to the reverse logistics' network, or possibly multiple retailers or suppliers. The relaxation of many of these assumptions will lead to models that more accurately represent real-world environments and would further assist in understanding such complex systems and coming up with various insights.

Bonney and Jaber (2011) argued the necessity to encompass environmental thinking into supply chain management. From here the focus of this analysis shall highlight the environmental thinking in reverse logistics. Definitions for green and sustainable supply chain management are presented in Ahi and Searcy (2013). They showed through their analysis that sustainable supply chain management is an extension of green supply chain management. Regardless of the overlaps in various definitions, what is important is the fact that environmental concerns are an important component of achieving sustainability for any business or organization. Sarkis et al. (2011) defined green supply chain management as the integration of environmental concerns into the inter-organizational practices of supply chain management including reverse logistics. Bei and Linyan (2005) and De Brito and Dekker (2003) showed that the underlying difference between green supply chains and reverse logistics is that reverse logistics focuses on the economic benefits of the recovery options. Consequently, these costs should no longer be ignored (Linton et al., 2007). Zhu and Sarkis (2003) and Ferretti et al. (2007) showed that the greening supply chain activities has benefits including saving of resources, reducing energy costs, reducing waste and pollution amongst other benefits. Van Hoek (1999) has looked into the reverse logistics as a research point that can be expanded to other research areas in green supply chain management. Marsillac (2008) showed that utilizing reverse logistics to manage returned items coincide with being environmentally friendly and further suggests that the integration of reverse logistics and green supply chain management into a comprehensive system. As a result, mathematical modelling of inventory models in reverse logistics should address these environmental aspects in order to realize the possible benefits and possible areas of improvement to achieve sustainability. The current literature shows that operationalizing such integration is not evident without mathematical models accounting for environmental aspects. The remainder of this section shall explore these various extensions from an environmental perspective.

There are numerous issues concerning the environment that are present in a supply chain. From the literature reviewed for this study, it is evident that the only environmental concern is that of wasted product, and even this is only considered as a disposal cost. Many environmental factors may arise from the disposal of waste product, including use of landfill and the issue of biodegradability. This has only been recently tapped into by Matar et al. (2014). Moreover, products consist of assemblies and components of which some could have liquids and/or gases that may be toxic or may contain other harmful materials. An interesting perspective that should be given attention is the concept of learning in production and inventory environments and product quality (Jaber and Bonney, 1998; 2003); Jaber et al., 2008). As workers 'learn' good manufacturing practices, correct procedures, etc., the amount of defects and subsequently solid waste can be reduced. Even further, learning in inspection and its effect on determining accepted quality products in inventory models has also been investigated (Khan et al., 2010) and could be looked into further to see their effects on solid waste and the impact it has on the environment. El Saadany et al. (2011) listed qualitative and quantitative environmental performance measures for a supply chain. Quantitative performance measures are categorized as financial and as those of polluting effects such as solid waste, air emissions, water waste, chemical waste, energy used and thermal pollution. The key question becomes how to operationalize these environmental issues and incorporate them into a reverse logistics of a supply chain model.

One environmental issue that has been given efforts is the modelling of greenhouse-gas (GHG) emissions. One obvious source of GHG emissions is from the transportation of goods. It has been modelled by Wahab et al. (2011) for domestic and international/overseas supply chains considering fixed and variable carbon emission costs. Further, Kannan et al. (2012) proposed a model that minimizes the carbon footprint, thus combining location and transportation in the decision problem. Another source of GHG emissions is from the production process, which has been investigated by Glock et al. (2012) and Jaber et al. (2013). Jaber et al. (2013) further considered an emissions penalty and trading scheme employed by the European Union. Such investigations are not present in reverse logistic models. Zanoni et al. (2014a, 2014b) investigated the use of energy in a two-stage production system (resembling a supply chain), where Bazan et al. (2015a) investigated the effects of emissions from production and transportation and energy usage on inventory coordination policies in a two level supply chain. Again, this has not been investigated in the context of a reverse logistics network. In the literature, there are works that show the energy used in production or relates it to the production rate of a process for machine tools (Gutowski et al., 2006; Mouzon et al., 2007) and steel plants (Nolde and Morari, 2010). Most of these works are empirical investigations to produce formulae that relate energy usage as a dependent variable and machine speed as an independent variable. They also showed that energy-related costs do affect the production and inventory policies. In addition, the energy consumption of products throughout their life, the energy required for production and technology advancements coupled with policies such as the consideration of leasing a product to customers instead of a final sale may have considerable environmental effects (Intlekofer et al., 2010). Similar investigations need to be performed to determine the energy required for recovery activities in order to capture the true environmental impact of energy on a production and inventory process.

Though complicated, the literature suggests that modelling of GHG emissions from transportation and production, energy usage from production and storage activities, as well as product/material waste disposal can be done. However, once investigated, the need for a comprehensive breakdown and modelling of a true reverse logistics (closed-loop supply chain) is required; i.e., a network that includes collection, inspection, separation, disassembly, reuse, repair, remanufacturing, and recycling operations. Each of these operations assists in the recovery or partial recovery of a returned product and each will be associated with product/component wastes, material wastes, GHG emissions, and energy used amongst others. Konstantaras et al. (2010) considered inspection and sorting with the recovery activities of a product, but more is needed to be considered. For example, the transportation of returned products and materials also need to be considered and should extend beyond the transportation distance. The type of fuel used and the mode of transportation not only affect the cost, but GHG emissions and depletion of natural resources as well. The consideration of these issues will show that the use of existing facilities and/or separate facilities for reverse logistics may have an economic and/or environmental trade-off. Moreover, such investigations can lead to further research in the recovery of products, material and, possibly, energy. As evident from the gaps presented in Table C3, there is a variety of directions that need to be addressed as earlier discussed.

Chapter 3

PROBLEM DEFINITION, OBJECTIVES AND APPROACH

The following chapter presents the objectives of this thesis and the approach taken.

3.1 Research Gaps

The overall conceptualization of this research is to provide a practical tool that can be used by business and organizations in the industry to allow them to improve the environmental performance of their supply chain operations without impeding its economic goals. Decision making is critical, and quantitative tools are essential to successful evaluations and corresponding decision making. The fundamental questions that arise are what contributions does a supply chain have to the environment, how can we measure these contributions, and finally how can these environmental concerns be controlled through supply chain operations. Answering these questions provides the opportunity to then improve and enhance the operational elements of a supply chain.

Generally, supply chain modelling has been an issue that has responded to financial pressures. Supply chains were optimized with the general objective to minimize total costs (Glock, 2012; Jaber and Zolfaghari, 2008]. Sustainability issues are becoming more and more prevalent and environmental concerns are required to be addressed (Bonney and Jaber, 2014; Sarkis, 2003, Srivastava, 2007). Frameworks suggest the incorporation of environmental issues to address these requirements, but mathematical modelling of supply chains and inventories in particular have only considered GHG emissions and their repercussions. Two main sources of GHG emissions are the production and transportation processes, which have not been jointly considered in EOQ and JELS models. The importance of energy consumption and its environmental impact regarding depleting resources, possible GHG emissions from generating this energy (especially from non-renewable sources), in addition to their increasing cost is an issue that has only been addressed on a micro-operation scale considering the efficiency of machines, but has been ignored in supply chain EOQ and JELS models. Essentially, the literature pertaining to the modelling of supply chains needs to integrate energy coupled with GHG emissions from both production and transportation operations to account for a more comprehensive picture that accurately accounts for the true cost of the supply chain and allows for a more responsible approach to supply chain policies and decision-making practices. Different coordination schemes may improve the financial performance of various supply chains under specific conditions and accordingly the investigation of such schemes should be attended to.

To respond to environmental pressures, mathematical modeling of reverse logistics has to account for these ignored costs. The reverse logistics models available in the literature are based on the EOQ model and only consider solid waste disposal of returned that cannot be recovered. Further, traditional inventory models (forward supply chain models), in general, have recently focused on greenhouse-gas (GHG) emissions as their environmental issue (Hua et al., 2011; Wahab et al., 2011; Jaber et al., 2013; Zanoni et al., 2014a). There is a disparity between the EOQ-based reverse logistics models and the environmental effects the respective models should account for. This paper looks to narrow this disparity and provide a model that accounts for the impact of several environmental issues and shows how inventory policies may require adjustments to lessen their environmental impact while retaining, to the best possible, the economic benefits.

The adverse effect that GHG emissions has on the environment is discussed in Kruger and Pizer (2004), IPCC (2006), Mouzon and Yildirim (2008) and Kaygusuz (2009). In this paper, GHG emissions come from manufacturing, remanufacturing, and shipping items to and collecting used items from the market. In addition, energy consumption from manufacturing also has a significant and negative impact on the environment (Devoldere et al., 2007; Mouzon and Yildirim, 2008; Dietmair and Verl, 2009). Coupled with the aforementioned solid waste disposal, which is the main environmental issue addressed in the available reverse logistics mathematical models, GHG emissions and energy used for manufacturing and remanufacturing are considered.

Addressing the research gaps, this thesis extends and compares the works of Jaber et al. (2013) and Zanoni et al. (2014a) by developing mathematical models for a two-level supply chain between a manufacturer (vendor) and buyer (retailer) that considers energy used for production, GHG emissions from production, and GHG emissions from transportation. Similarly a reverse logistics mathematical model presented in this thesis accounts for these three main environmental issues. These models are further extended by combining them to present a closed loop supply chain model that consider a classical coordination scheme and a VMI with CS policy.

Figure 3.1 summarizes the selection of industry, supply chain model, and coordination schemes where the thick borders and highlighted boxes constitute the considerations and boundaries of the study pertaining to this research.

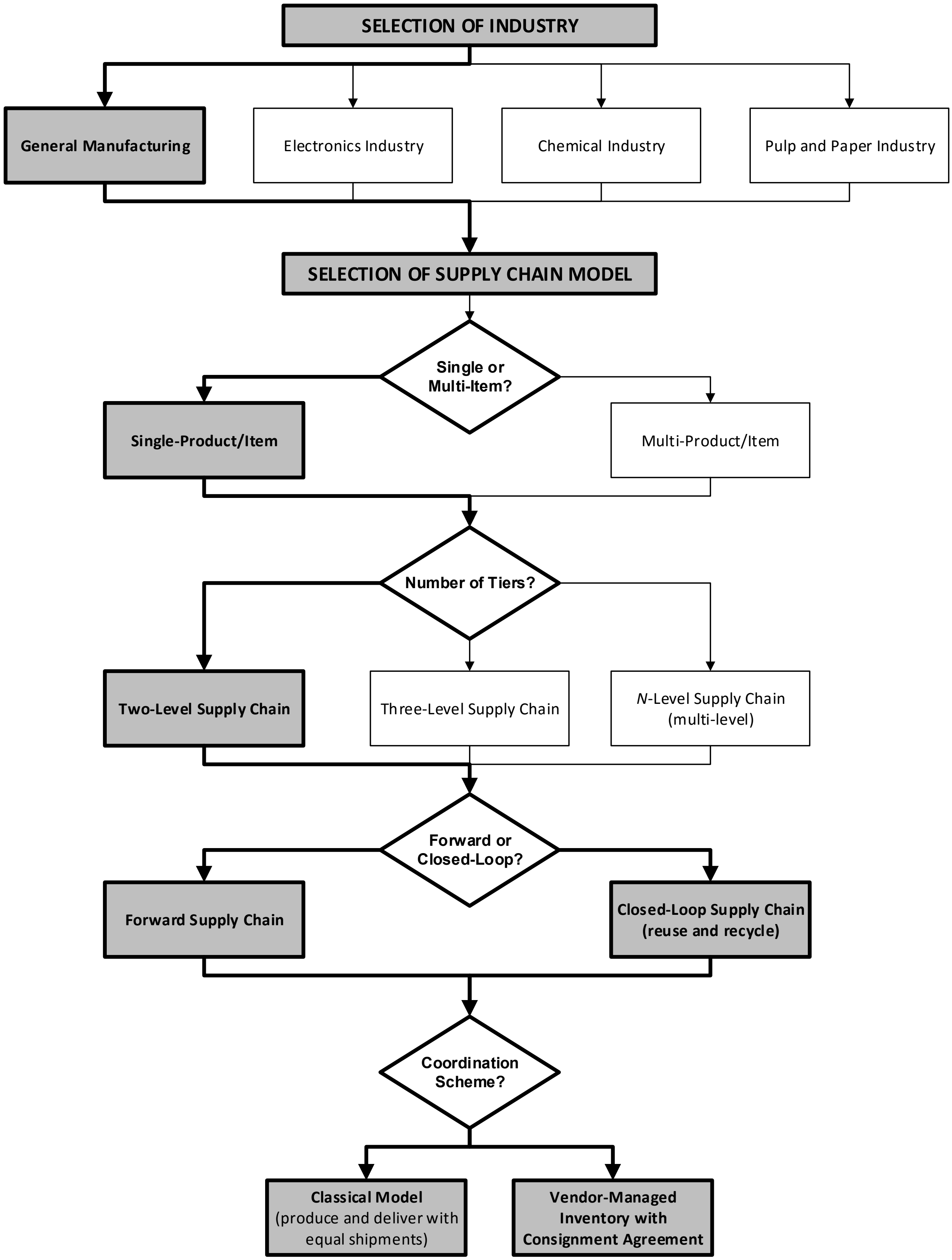

Figure 3.1 *Research considerations and study scope*

3.2. Approach

The development of each supply chain (inventory) model follows a four stage approach as outlined in Figure 3.2. Stages 1 and 2 focus on the performance measures and relating them to the decision variables of the system. Stage 3 is the actual development of the model including both validation and verification of the system and the mathematics involved. Stage 4 is the final stage in which the system is optimized and results are obtained for analyses.

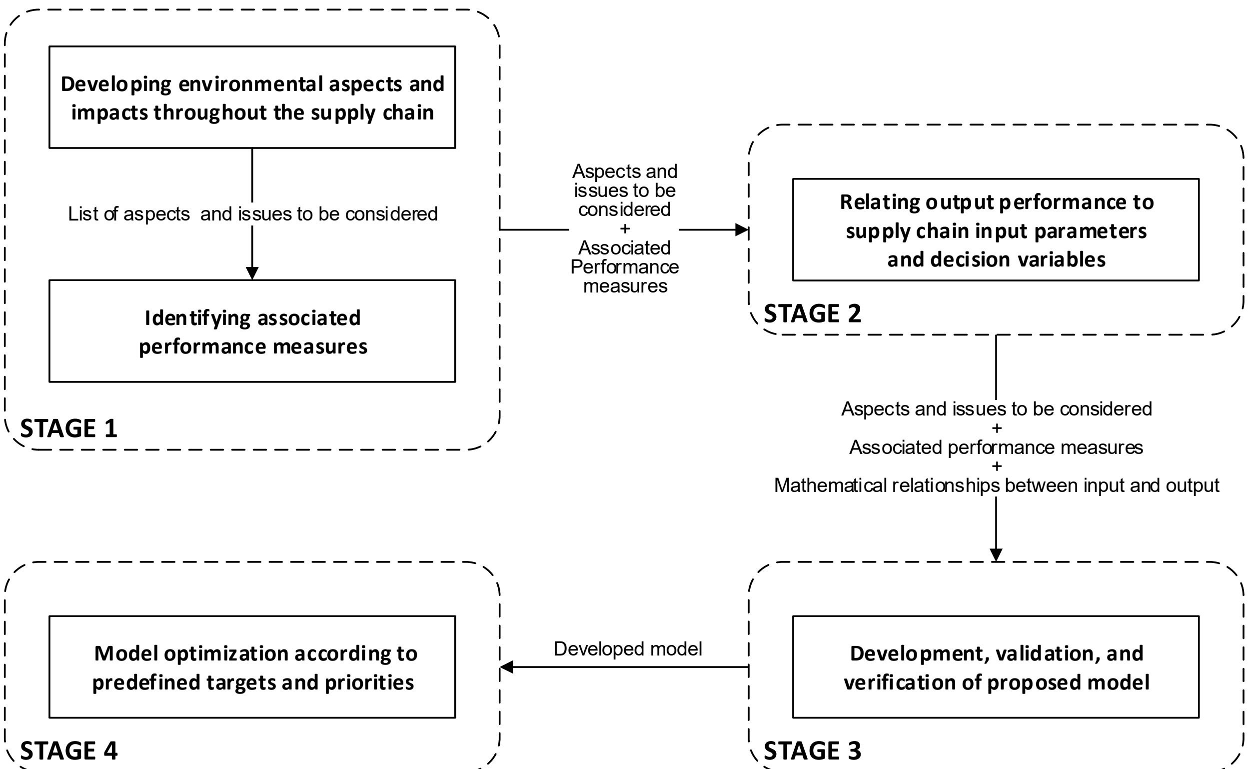

Fig 3.2 *Flowchart for modeling and optimizing environmentally responsible supply chains*

3.3. Objectives

In brief, this thesis shall provide tools that can help analyze and optimize supply chain operations from both economic and environmental perspectives. In order to address the gaps presented in the literature the following objectives are set for this research:

- To analyze supply chain systems to determine how they affect and impact the environment
- To determine mathematical relationships to quantify the environmental and economic performance of a supply chain
- To develop models that can quantitatively assess the performance of a supply chain environmentally and economically
- To optimize a supply chain's performance collectively from both an economic and environmental perspective

3.4 Organization of Thesis

The remainder of this thesis is organized as follows. Chapter 4 presents two supply chain models incorporating different coordination policies. Chapter 5 presents a reverse logistics inventory model. Chapter 6 combines the models presented in Chapter 4 and 5 to develop a closed-loop supply chain model accounting for environmental concerns. Conclusions and future research extensions are presented in chapter 7.

Chapter 4

SUPPLY CHAIN MODELS WITH GREENHOUSE GASES EMISSIONS, ENERGY USAGE AND DIFFERENT COORDINATION DECISIONS

This chapter presents two models. A two-level supply chain model with a classical coordination and a two-level supply chain with a VMI-CS coordination. Elements of this chapter are taken from Bazan et al. (2015a).

4.1 Introduction

This section starts by presenting the necessary notations, followed by a brief exposition of the models of Jaber et al. (2013) and Zanoni et al. (2014a). Both papers describe a two-level supply chain with a manufacturer (vendor) and a buyer with GHG emissions (mainly CO2) generated from the production process, but with different coordination mechanisms: classical coordination and consignment stock agreement, respectively. After presenting the mathematics, we modify both models to include emissions from transportation (with applicable emissions penalties), and energy consumed/used in the production of items. The objective for each model is to find the optimal production rate (subsequently the joint-lot sizing policy), and subsequently, the number and size of shipments from the manufacturer to the retailer that minimizes the total supply chain cost. It is worth noting that the number and size of shipments in the presence of truck capacity affect the number of truck-trips required per year and, subsequently, the transportation costs and emissions generated from transportation activities. The next sections list the notations, decision variables, make assumptions where necessary, and modify the mathematical models, respectively.

4.2 Base-Model I: Classical coordination

The base model is that of Jaber et al. (2013), which represents a coordinated two-level supply chain for a single product that accounts for GHG emissions from manufacturing processes with different emissions trading schemes. This model could assist decision makers in minimizing inventory related and CO2 emissions costs of a supply chain, especially when penalties for exceeding emissions limits are considered. The notations used in Jaber et al. (2013) are:

Input parameters:

d	demand rate (unit/year);
h_m	holding cost at the manufacturer's side ($/unit/year);
h_r	holding cost at the retailer's side ($/unit/year);
S_m	manufacturer's setup cost ($);
S_r	retailer's fixed ordering cost ($);
a	emissions function parameter (ton·year^2/unit^3);
b	emissions function parameter (ton·year/unit^2);
c	emissions function parameter (ton/unit);
E	greenhouse gas (CO2) emissions (ton/unit);
E_{li}	emissions limit i (ton/year);
n	number of emissions limits;
C_{ec}	emissions tax ($/ton);
$C_{ep,i}$	emissions penalty ($/year) for exceeding emissions limit i;
α	minimum production-demand ratio, where $\alpha > 1$;
P_{min}	minimum production rate (unit/year), where $P_{min} = \alpha d$;
P_{max}	maximum attainable production rate (unit/year);

Decision variables:

P	manufacturer's production rate, where $P_{min} \leq P \leq P_{max}$ (unit/year);
λ	manufacturer-retailer coordination multiplier, where $\lambda \geq 1$ (integer); number of shipments of size q in a manufacturer's cycle

In this model, the manufacturer delivers λ shipments of equal batch size q to the retailer to satisfy the supply chain demand d over the cycle time T, where $= \frac{\lambda q}{d}$. The behaviour of inventory levels at the manufacturer and the retailer is illustrated in Fig. 4.1.

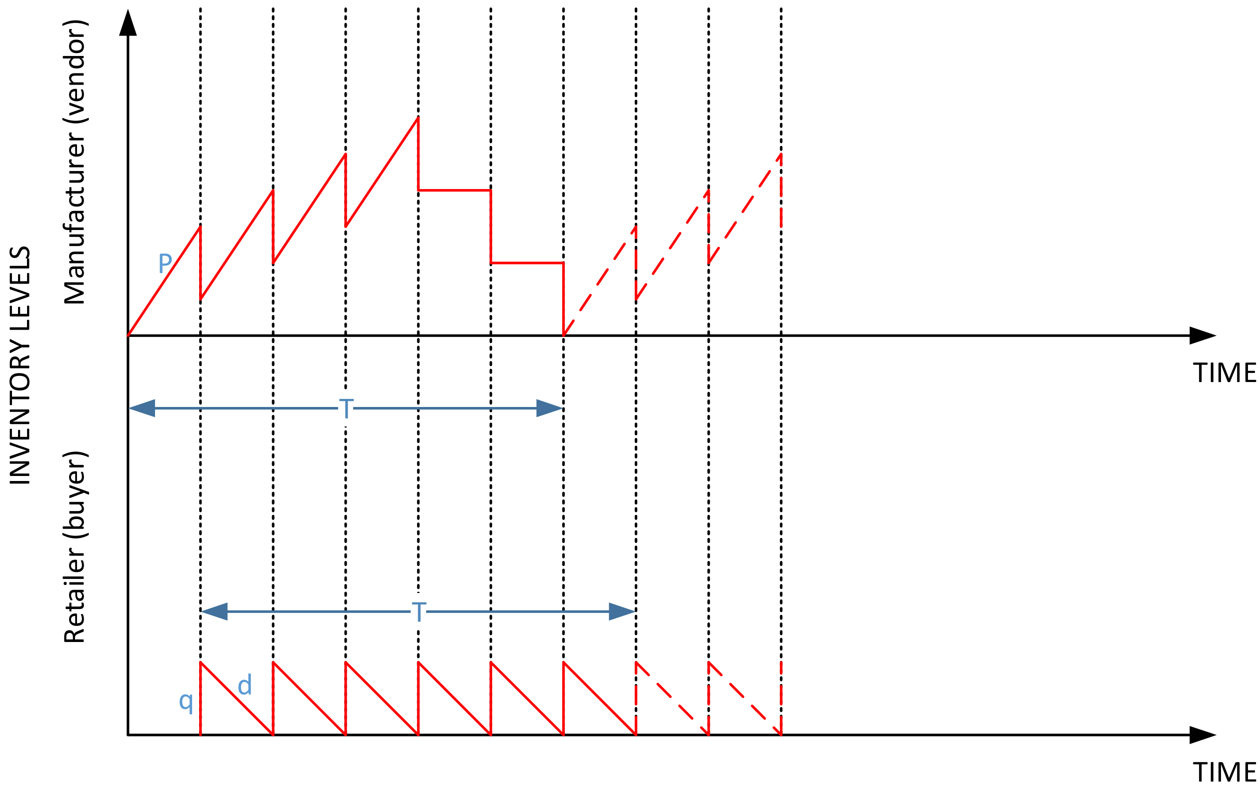

Figure 4.1. *Inventory levels for a coordinated two-level supply chain with λ=6 (dashed line indicates the next inventory cycle).*

The supply chain cost is the sum of the following per unit of time costs: the manufacturer's and retailer's holding costs, along with the manufacturer's setup cost and the retailer's fixed ordering cost. These costs can be presented as a function of arguments P and λ and is written as (Jaber et al., 2013):

$$SC_1(P,\lambda) = \sqrt{2d(S_m + \lambda S_r)\left[h_m\left(1 - \frac{d}{P} + \frac{1}{\lambda}\right) + \frac{h_r}{\lambda}\right]} \tag{4.1}$$

The optimal number of items shipped per batch can be written as (Jaber et al., 2013):

$$q(P,\lambda) = \sqrt{\frac{2d\left(\frac{S_m}{\lambda}+S_r\right)}{h_m\left[1+\lambda\left(1-\frac{d}{P}\right)\right]+h_r}} \tag{4.2}$$

Note that Eq. (4.1) is reduced from $SC_1(P,\lambda,q) = \frac{S_m d}{\lambda q} + h_m \frac{q}{2}\left[1+\lambda\left(1-\frac{d}{P}\right)\right] + \frac{S_r d}{q} + h_r \frac{q}{2}$ after substituting for q given in Eq. (4.2), where $\frac{\partial^2}{\partial q^2} SC_1(P,\lambda,q) = \frac{2S_m d}{\lambda q^3} + \frac{2S_r d}{q^3} > 0 \quad \forall q > 0$ and $\frac{\partial^2}{\partial \lambda^2} SC_1(P,\lambda,q) = \frac{2S_m d}{\lambda^3 q} > 0 \ \forall \lambda > 0$, where Eq. (4.1) is separately convex in λ for a fixed value of P.

The amount of CO_2 emissions (ton/unit) from a production process (see Jaber et al., 2013) is calculated as:

$$E(P) = aP^2 - bP + c \tag{4.3}$$

where a, b, and c can be empirically validated: Narita (2012) showed how to analyse the environmental burden of operating a machine tool and presented a relationship of equivalent CO_2 emissions to be of the same form as that presented in Eq. (4.3) above; see Eq. (10) on page 258 in Narita (2012). Narita's (2012) experiments showed that as the cutting speed is increased, the tool wear becomes significantly higher and thus the tool life is shortened, which increases the associated environmental burden (in terms of equivalent CO_2 emissions). However, the environmental burden associated with the electrical consumption of the machine tool, the lubricant and cooling liquid is proportionate to time, which indicates that there is a trade-off relationship with respect to the cutting speed. The behaviour of the equivalent CO_2 emitted is approximated by a quadratic equation that can be represented by Eq. (43). This can be seen in Fig. 4.2. This is important as in the developed model we will be considering a machine tool as the reference equipment for the manufacturer's production facility.

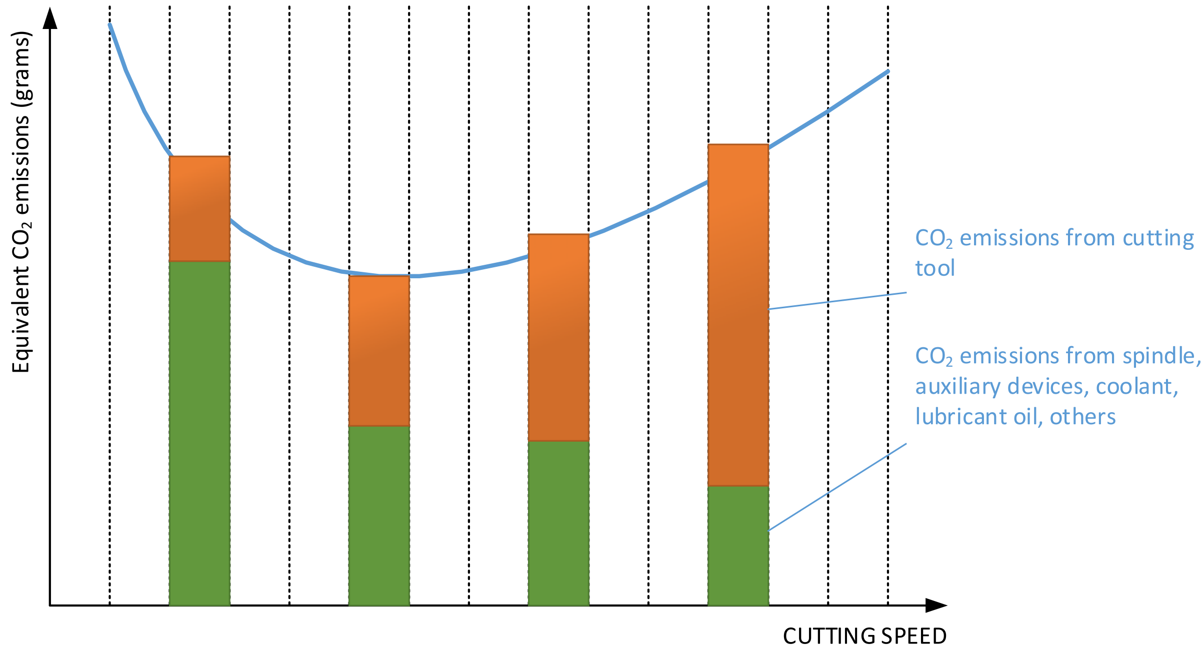

Figure 4.2. *Equivalent CO2 emissions from a machine tool at various cutting speeds (a reproduction of Fig. 6 in Narita (2012) page 257).*

The CO_2 emissions cost from production can be written as:

$$EC_1 = EdC_{ec} \tag{4.4}$$

Penalties from CO_2 emissions are applied such that a penalty cost is accrued when the amount of CO_2 emissions produced exceeds the specified limits (similar to Jaber et al., 2013). Accordingly, the penalty cost for CO_2 emissions can be written as:

$$EC_3 = \sum_{i=1}^{n} Y_i C_{ep,i} \tag{4.5}$$

where

$$Y_i = 1,\ \text{if } Ed > E_{li}\ (i = 1, 2, \ldots, n), \text{ and } Y_i = 0, \text{ otherwise} \tag{4.6}$$

The term EC_2 is reserved for the cost of CO_2 emissions from transporting goods, which will also be incorporated to calculate the total emissions to determine if they exceed the specified limits and contribute to EC_3. This will be accounted for and explained later in Section 4.4.

The total cost of the system can then be given by the summation of the costs SC1, EC1, and EC3 and can be written as (Jaber et al,, 2013):

$$TC_1(P,\lambda) = \sqrt{2d(S_m + \lambda S_r)\left[h_m\left(1 - \frac{d}{P} + \frac{1}{\lambda}\right) + \frac{h_r}{\lambda}\right]} + (aP^2 - bP + c)dC_{ec} + \sum_{i=1}^{n} Y_i C_{ep,i} \quad (4.7)$$

4.3 Base-Model II: Consignment-stock agreement

Base model II is that of Zanoni et al. (2014a), which investigated the work of Jaber et al. (2013) for a different coordination mechanism, namely, the vendor-managed inventory (VMI) with consignment-stock (CS) policy. The manufacturer in this case produces λq items and ships each q immediately upon production to the retailer. The retailer then consumes the items. The inventory behaviour at both the manufacturer and the retailer is illustrated in Fig. 4.3. In addition to the notations used above, Zanoni et al. (2014a) model uses the following additional notations:

h_m^{fin} financial component of the manufacturer's holding cost (\$/unit/year);

h_m^{ph} physical component of the manufacturer's holding cost (\$/unit/year);

h_r^{fin} financial component of the retailer's holding cost (\$/unit/year);

h_r^{ph} physical component of the retailer's holding cost (\$/unit/year).

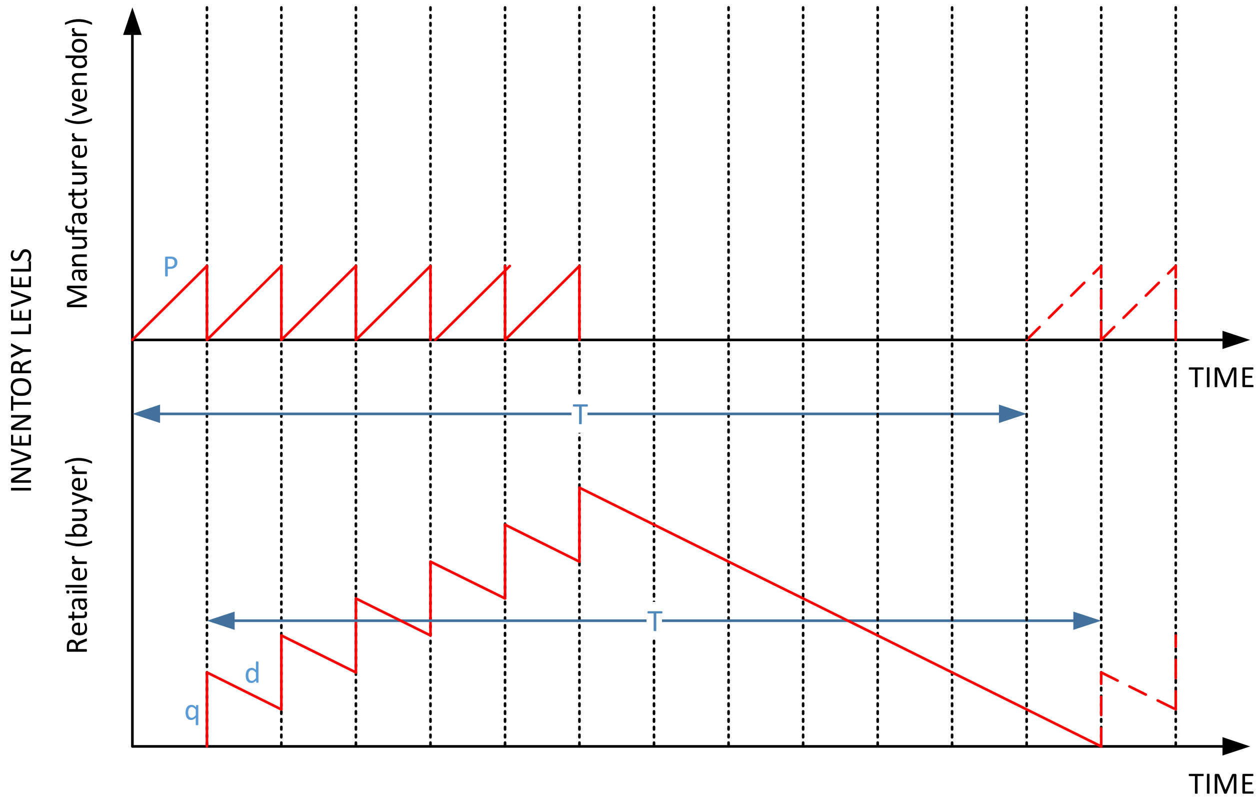

Figure 4.3. *Inventory levels for a two-level supply chain with VMI-CS policy with λ=6 (dashed line indicates the next inventory cycle).*

In a VMI with CS policy the financial cost of holding inventory at the retailer's side is charged to the vendor but the manufacturer remains responsible for the physical storage inventory cost (Zanoni et al., 2014a).

The supply chain cost is the sum of the following costs per unit of time: the holding cost at the manufacturer's side and retailer's side, along with the manufacturer's setup cost and the retailer's fixed ordering cost. These costs can be written as (Zanoni et al., 2014a):

$$SC_2(P,\lambda) = 2\sqrt{\frac{d(S_m+\lambda S_r)}{\lambda}\left[\left(h_m^{fin}+h_r^{ph}\right)\left(\frac{d}{P}+\frac{(P-d)\lambda}{2P}\right)+\frac{\left(h_m^{ph}-h_r^{ph}\right)d}{2P}\right]} \quad (4.8)$$

The optimal number of units shipped per batch is written as (Zanoni et al., 2014a):

$$q(P,\lambda) = \sqrt{\frac{d(S_m+\lambda S_r)}{\lambda\left[\left(h_m^{fin}+h_r^{ph}\right)\left(\frac{d}{P}+\frac{(P-d)\lambda}{2P}\right)+\frac{\left(h_m^{ph}-h_r^{ph}\right)d}{2P}\right]}} \tag{4.9}$$

Note that Eq. (4.8) is reduced to its form in a similar manner as explained for Eq. (4.1) but with the substitution for q that is given in Eq. (4.9) in the following $SC_2(P,\lambda,q) = \frac{d(S_m+\lambda S_r)}{\lambda q} + \left(h_m^{fin} + h_m^{ph}\right)\left[\frac{dq}{P} + \frac{(P-d)\lambda q}{2P}\right] + \frac{\left(h_m^{ph}-h_r^{ph}\right)qd}{2P}$ from (Braglia and Zavanella, 2003).

It should be noted that there is a typographical mistake from Eq. (4) onwards in Zanoni et al. (2014a), where instead of having the term $\left(h_m^{fin} + h_r^{ph}\right)$ in Eqs. (8-10) they have the term $\left(h_m = h_m^{fin} + h_m^{ph}\right)$. The correct term could be easily derived starting with Eq. (3) in Zanoni et al. (2014a), which was directly derived from Braglia and Zavanella (2003). However, we would point out that the numerical analysis reported in Zanoni et al. (2014a) was not affected by the typographical mistake.

The amount of CO_2 emissions from production and the annual cost are calculated with Eqs. (4.3) and (4.4), respectively, where Eqs. (4.5) and (4.6) account for the penalty costs for exceeding the CO_2 emissions, respectively. The total cost of the system can then be given by the summation of the costs SC_2, EC_1, and EC_3 and can be written as (Zanoni et al., 2014a):

$$TC_2(P,\lambda) = 2\sqrt{\left(\frac{d(S_m+\lambda S_r)}{\lambda}\right)\left[\left(h_m^{fin} + h_r^{ph}\right)\left(\frac{d}{P} + \frac{(P-d)\lambda}{2P}\right) + \frac{\left(h_m^{ph}-h_r^{ph}\right)d}{2P}\right]}$$
$$+(aP^2 - bP + c)dC_{ec} + \sum_{i=1}^{n} Y_i C_{ep,i} \tag{4.10}$$

4.4 CO_2 emissions from transporting goods

An integral part of any supply chain is the transportation of goods from one entity to the next. Transportation is considered the largest component of distribution or logistics costs (Allen, 1997). There are numerous forms of transport modes that can be used in logistics (Tseng et al., 2005).

This paper focuses on land logistics and specifically road freight. There are advantages to road freight that include cheap costs, high accessibility, availability and mobility, and disadvantages such as low capacity, reduced safety, and slower speeds (Tseng et al., 2005). Of specific concern is the issue of traffic congestions causing pollution, particularly the contribution of CO2 emissions to the environment (Gorham, 2002; Tseng et al., 2005). This section focuses on and explains how CO2 emissions from transportation are calculated. The following additional notations are used:

g	fuel volume required per truck per trip (gallons);
e_t	amount of CO2 emissions from fuel per gallon consumed (ton/gallon);
t_c	truck capacity (units/truck);
η	number of trucks of capacity tc per shipment; an integer and a decision variable;
E_{tr}	amount of CO2 emissions from transportation.

The total amount of CO2 emissions from all trucks per year is calculated as:

$$E_{tr} = \eta\lambda \frac{d}{\lambda q} g e_t = \eta \frac{d}{q} g e_t \tag{4.11}$$

Although η could be represented as a function of q, $\eta = \left\lceil \frac{q}{t_c} \right\rceil$, it is treated as a decision variable. The rationale for doing so is provided later in the chapter, following Eq. (4.18). The cost of CO_2 emissions from transportation is, thus, calculated as:

$$EC_2 = E_{tr} C_{ec} \tag{4.12}$$

This additional source of CO_2 emissions to the system is accounted for as it may result in exceeding the permissible emissions limit. Consequently, Eq. (5) is adjusted such that:

$$Y_i = 1, \text{ if } (Ed + E_{tr}) > E_{li} \ (i = 1, 2, \dots, n), \text{ and } \quad Y_i = 0, \text{ otherwise} \tag{4.13}$$

4.5 Transportation cost

The assumption of a single-vendor and a single-buyer scenario implies that the transportation cost per shipment can be a constant value per truck per shipment (Bozorgi et al., 2014). Since the distance between the vendor and the buyer remains fixed, and assuming that the fuel price is a constant, the cost of fuel can then be incorporated into the fixed transportation cost per truck. The cost of transportation per year is thus calculated as:

$$SC_{transport} = C_t \eta \lambda \left(\frac{d}{\lambda q}\right) = \eta C_t \frac{d}{q} \tag{4.14}$$

where C_t is a fixed cost of truck per shipment ($/truck). Accordingly, the supply chain cost is to be adjusted to account for the cost of transportation and consequently Eqs. (4.1), (4.2), (4.7) for the classical coordination and Eqs. (4.8–4.10) for the VMI-CS coordination policy are respectively adjusted as presented later in Eqs. (4.17–4.20) of Sections 4.7.1 and 4.7.2.

4.6 Specific energy usage

The industrial sector is the largest consumer of energy (http://www.eia.gov/forecasts/aeo/pdf/0383(2012).pdf). In addition to the increase in energy costs there are significant environmental impact associated with the consumption of energy (Mouzon et al., 2007; Ross, 1992]. With the majority of energy resources being non-renewable, energy usage is of more concern as it represents an environmental burden. This section explains how energy usage is accounted for in the model. The following additional notations are used:

- C_0' coefficient of the inverse model (KWh/unit);
- C_1' coefficient of the predictor (KWh/year);
- SEC specific energy consumed (KWh/unit);
- C_{en} cost of specific energy ($/KWh).

For this study, the manufacturer's facility consists of machine tools. The function of a machine tool is to remove material (in various forms, depending on the machine tool) and thus the material removal rate (MRR) is assumed to be equivalent to the manufacturer's production rate P, where MRR is measured in cm^3 per second. To illustrate, if the MRR is 0.2 cm^3/s and the total material removed per unit is 200 cm^3, then the production rate is computed as 3.6 units/hr (for this case it can be assumed that loading/unloading times are negligible). Currently, energy use in manufacturing can only be estimated empirically (Drake et al, 2006; Li and Kara, 2011). Energy analyses showed that the energy requirements of actual material removal could be quite small when compared to the total energy associated with machine tool operations (Li and Kara, 2011; Dahmus and Gutowski, 2004). This empirical approach treated the machine tool as a whole system, capturing the relationship between energy used and the number of units processed by means of two coefficients C_0 and C_1. Li and Kara (2011) provided values for C_0 and C_1 in terms of MRR in cm^3 per second, which have been adjusted to C_0' and C_1' in order to express the production rate in terms of units per year and energy in kilowatt-hours (see Appendix D). Adopting this relationship allows the specific energy consumed per unit produced to be written as:

$$SEC(P) = C_0' + \frac{C_1'}{P} \tag{4.15}$$

where C_0' (associated with work-piece material, tool geometrics, spindle drive characteristics), and C_1' (associated with the machine tool) are parameters. It is very difficult to assign values to C_0 and C_1 with precision; however, a procedure on how to do so is explained in Li and Kara (2011). Once the values of C_0 and C_1 are obtained, the empirical model can predict the energy consumed for production with significant accuracy (Li and Kara, 2011). Accordingly, the cost of energy for production is calculated by:

$$EC_4 = SEC(P)dC_{en} \tag{4.16}$$

It should be noted that the cost of energy from the supplier includes the GHG emissions cost as well as all other associated costs with the procurement of energy; however, this does not include the cost of GHG emissions produced by the machine itself (i.e. does not include EC_1, calculated by Eq. (4.4)).

4.7 Model statement

The developed modelling approach accounts for the supply chain costs and the costs of the environmental factors presented in the previous sections. There are two models presented based on the classical coordination policy and the VMI with CS policy.

4.7.1 Classical coordination policy

The total system cost (with the classical coordination policy) in Eq. (7) is now the sum of SC_1 (adjusted to include the transportation cost), EC_1, EC_2, EC_3, and EC_4, that is:

$$TC_1(P,\lambda,q,\eta) = \frac{S_m d}{\lambda q} + h_m \frac{q}{2}\left[1 + \lambda\left(1 - \frac{d}{P}\right)\right] + \frac{S_r d}{q} + h_r \frac{q}{2} + (aP^2 - bP + c)dC_{ec} + \eta \frac{d}{q} g e_t$$
$$+ \sum_{i=1}^{n} Y_i C_{ep,i} + \left(C_0' + \frac{C_1'}{P}\right) dC_{en}$$

which reduces to:

$$TC_1(P,\lambda,\eta) = \sqrt{2d(S_m + \eta C_t \lambda + \lambda S_r)\left[h_m\left(1 - \frac{d}{P} + \frac{1}{\lambda}\right) + \frac{h_r}{\lambda}\right]} + (aP^2 - bP + c)dC_{ec} +$$
$$\eta g e_t C_{ec} \sqrt{\frac{d\left(h_m\left[1+\lambda\left(1-\frac{d}{P}\right)\right]+h_r\right)}{2\left(\frac{S_m}{\lambda}+\eta C_t + S_r\right)}} + \sum_{i=1}^{n} Y_i C_{ep,i} + \left(C_0' + \frac{C_1'}{P}\right) dC_{en} \qquad (4.17)$$

after substituting the optimal number of units shipped per batch for the classical coordination, $q(P,\lambda)$, in $TC_1(P,\lambda,q,\eta)$. $q(P,\lambda,\eta)$ is given as:

$$q(P,\lambda,\eta) = \sqrt{\frac{2d\left(\frac{S_m}{\lambda}+\eta C_t + S_r\right)}{h_m\left[1+\lambda\left(1-\frac{d}{P}\right)\right]+h_r}} \qquad (4.18)$$

where Y_i is given by Eq. (4.13). Note that although η was not intended to be a decision variable, we found having it as $\eta = \left\lceil \frac{q}{t_c} \right\rceil$ would make finding a closed form solution for Eq. (4.17) and later (4.19) difficult. So, we decided to treat it as decision variable as we found it easier this way; however, we introduced the following constraint $\eta t_c - q \geq 0$, which has the same logic as $\eta = \left\lceil \frac{q}{t_c} \right\rceil$.

1. To optimise Eq. (4.17), and later Eq. (4.19) we followed a very similar solution procedure like the one described in Jaber and Goyal (2008). The steps are:

2. Start by setting η = 1 and $\lambda = 1$, then searching for different values of P, $q(P,1,,1)$ is calculated and subsequently $TC_1(P,1,1)$, while $\eta t_c - q \geq 0$. The search stops when the minimum of $TC_1(P_1,1,1)$, is reached, naming P_1 the optimal value of P of trial 1, and $Value\ 1 = TC_1(P_1,1,1)$.

3. The process is repeated for $\eta = 1$ and $\lambda = 2$, searching again for the minimum of TC_1, naming P_2 the optimal value of P in trial 2, with $Value\ 2 = TC_1(P_2,1,1)$.

4. If $Value\ 1 < Value\ 2$, then the $Value\ 1 = TC_1(P_1,1,1)$, else $Value\ 1 = TC_1(P_2,2,1)$. This is repeated till optimal values of P and λ are found, such that $Value\ 1 = TC_1(P_i,\lambda_i,1)$.

5. Similarly, the procedure is repeated for $\eta = 2$ and $\lambda = 1$, $\eta = 2$ and $\lambda = 2$, etc. The $Value\ 2 = TC_1(P_j,\lambda_j,2)$ for a run in this (second) search cycle is compared with $Value\ 1$ obtained from the previous (first) search cycle; if $TC_1(P_i,\lambda_i,1) < TC_1(P_j,\lambda_j,2)$, then $Value\ 1 = TC_1(P_i,\lambda_i,1)$, else $Value\ 1 = TC_1(P_j,\lambda_j,2)$.

6. This procedure is repeated till we find the optimal values of P, λ and η for search cycle k, where $Value\ 1 = TC_1(P_k,\lambda_k,\eta_k)$.

To accelerate the search, values of λ that yields infeasible solutions are omitted from the search. This is done by finding the initial search value of λ that produces a feasible solution. This can be done by determining the value of λ in terms of q from $TC_1(P,\lambda,q,\eta)$ by setting its first partial derivative with respect to λ equal to zero and solving for λ to get $= \frac{1}{q}\sqrt{\frac{2S_m d}{h_m(1-d/P)}}$. From this relationship and $\eta t_c - q \geq 0$, we have $\lambda = \frac{1}{\eta t_c}\sqrt{\frac{2S_m d}{h_m(1-d/P)}}$, from which λ registers a maximum value, λ_m (q will be minimum) when $P = P_{min} = \alpha d$, and minimum, λ_{min} (q will be maximum), when $P = P_{max}$. So, the search can also start from $\eta = 1$ and $\lambda = \lambda_{max}$, where it will go from feasible points to infeasible ones. Note that details and examples are provided in Jaber and Goyal (2008, pp. 99-100).

4.7.2 VMI with CS Policy

The total system cost (with the classical coordination policy) in Eq. (4.10) is now the sum of SC_2 (adjusted to include the transportation cost), EC_1, EC_2, EC_3, and EC_4, that is:

$$TC_2(P,\lambda,q,\eta) = \frac{d(S_m+\lambda S_r)}{\lambda q} + \left(h_m^{fin}+h_m^{ph}\right)\left[\frac{dq}{P}+\frac{(P-d)\lambda q}{2P}\right] + \frac{\left(h_m^{ph}-h_r^{ph}\right)qd}{2P}$$
$$+ (aP^2-bP+c)dC_{ec} + \eta\frac{d}{q}ge_tC_{ec} + \sum_{i=1}^{n} Y_iC_{ep,i} + \left(C_0' + \frac{C_1'}{P}\right)dC_{en} \tag{4.19}$$

which reduces to:

$$TC_2(P,\lambda,\eta) = 2\sqrt{d\left(\frac{S_m}{\lambda}+\eta C_t+S_r\right)\left[\left(h_m^{fin}+h_r^{ph}\right)\left(\frac{d}{P}+\frac{(P-d)\lambda}{2P}\right)+\frac{\left(h_m^{ph}-h_r^{ph}\right)d}{2P}\right]}$$
$$+ (aP^2-bP+c)dC_{ec}$$
$$+ \eta ge_tC_{ec}\sqrt{\frac{d\left[\left(h_m^{fin}+h_r^{ph}\right)\left(\frac{d}{P}+\frac{(P-d)\lambda}{2P}\right)+\frac{\left(h_m^{ph}-h_r^{ph}\right)d}{2P}\right]}{\frac{S_m}{\lambda}+\eta C_t+S_r}}$$
$$+ \sum_{i=1}^{n} Y_iC_{ep,i} + \left(C_0' + \frac{C_1'}{P}\right)dC_{en} \tag{4.20}$$

after substituting the optimal number of items shipped per batch for the VMI-CS, $q(P,\lambda,\eta)$, in $TC_2(P,\lambda,q,\eta)$. $q(P,\lambda,\eta)$ is given as:

$$q(P,\lambda,\eta) = \sqrt{\frac{d\left(\frac{S_m}{\lambda}+\eta C_t+S_r\right)}{\left(h_m^{fin}+h_r^{ph}\right)\left(\frac{d}{P}+\frac{(P-d)\lambda}{2P}\right)+\frac{\left(h_m^{ph}-h_r^{ph}\right)d}{2P}}} \tag{4.21}$$

4.7.3 Optimization Model and Programming

The problem is a non-linear mixed integer programming problem that is solved by minimizing either Eqs. (4.17) or (4.19), depending on the type of the coordination policy applied, subject to

Eq. (4.13), $P_{min} \leq P \leq P_{max}$, $\eta \geq 1$ and integer, $\eta t_c - q \geq 0$, and $\lambda \geq 1$ and integer. The problem has been solved using Microsoft Excel (2013) with the Solver add-in enhanced with Visual Basic macros to solve for P, λ, η, and to perform associated sensitivity analyses. The values of q for the classical and VMI-CS policies are computed, respectively, from Eqs. (4.18) and (4.20) for values of P, λ, and η.

Eqs. (4.7) and (4.10), i.e., TC_1 and TC_2, where shown to be convex in q, λ, and P in Jaber et al. (2013) and Zanoni et al. (2014a), respectively. The sum of the additional costs EC_2 and EC_4 are convex in P. It can be easily shown by substituting the value of q, either from Eq. (4.2) or Eq. (4.9), in EC_2 that $EC_2 + EC_4$ is convex in P. So, we can conjuncture that Eqs. (4.17) and (4.19) are convex in q, λ, and P. Accordingly, the solution procedure is achieved by using the Microsoft Excel Problem Solver add-in to find P for given values of λ and η that yields the minimum total cost, as explained in the solution procedure following Eq. (4.18); also see Jaber and Goyal (2008, pp. 99-100).

4.8 Numerical examples

This section illustrates the operation of the developed models for both the classical coordination policy and the VMI-CS agreement policy. The purpose of the numerical examples is to investigate the effects of the various environmental factors on the supply chain model, and to show how business decisions can be more environmentally responsible. The values of the input parameters were obtained from real-world examples to resemble a real manufacturing environment.

4.8.1. Input parameters

Jaber et al. (2013) provided the base model for which the current model for the classical coordination has been developed. The input parameters regarding the supply chain parameters and the CO_2 emissions costs are adopted from their work. Accordingly, the following input values are set at: $d = 1000$ (unit/year); $h_m = 60$ (\$/unit/year); $h_r = 30$ (\$/unit/year); $S_m = 1200$ (\$);

$S_r = 400$ (\$); $C_{ec} = 18$ (\$/ton); $\alpha = 1.1$, $a = 0.0000003$ (ton·year²/unit³); $b = 0.0012$ (ton·year/unit²); c = 1.4 (ton·year/unit); and the emissions penalty schedule is given in Table 4.1.

Table 4.1. *Emission penalty schedule (from Jaber et al., 2013)*

i	Emission limit E_{li}	Penalty charged, C_{epi}
1	$Ed < 220$	0
2	$220 \le Ed < 330$	\$1000
3	$330 \le Ed < 440$	\$2000
4	$440 \le Ed < 550$	\$3000
5	$550 \le Ed < 660$	\$4000
6	$Ed \ge 660$	\$5000

Dahmus and Gutowski (2004) provided detailed machine specifications of a production machining center from which the following is assumed for Eq. (4.17) to be: $C_0' = 57.96$ KWh/unit and $C_1' = 361{,}275$ KWh/year (Appendix D). For the sake of argument, the cost of energy per KWh is obtained from BC-Hydro of British Colombia, Canada (www.bchydro.com), that is: $C_{en} = 0.0928$ \$/KWh.

According to the United States Environmental Protection Agency – Office of Transportation and Air Quality, the CO_2 emissions from diesel fuel per gallon consumed is: $e_t = 0.01008414$ tons/gallon. Assuming the distance travelled between the manufacturer and the retailer is 300 miles (Appendix E) and the truck is a Class 7 truck with an average fuel consumption being 4 miles per gallon (The National Academies, 2010), then the amount of fuel required per truck per trip (300 miles) can be given as: $g = 75$ gallons. Truck capacity is assumed at 80 units per truck, that is: $t_c = 80$ units, and the truck cost per shipment is calculated to be $C_t = \$400$ (Appendix F).

4.8.2 Results and discussion for classical coordination

Applying the model to the above parameters and by optimizing Eq. (4.17), TC_1, for P, η and λ, the optimal production scenario is: $P = 2396$, $\eta = 2$ and $\lambda = 2$ with a total system cost of $TC_1 = \$48002.44$. Table 4.2 illustrates how the search for the optimal solution was performed. The supply chain (financial and transportation) costs, $SC_1 = 23993.74$ (Eq. (4.1)), represent the majority of the total costs at about 50%, followed by Energy costs, $EC_4 = 19371.31$ (Eq. (4.16)), as the second largest component at 41%, with the remaining 9% being CO_2 emissions related costs ($EC_1 + EC_2 = 18(247.04 + 10.59) = \$4637.40$) (sum of Eqs. (4.4) and (4.12)). The majority of CO_2 emissions are from production, EC_1. The total amount of CO_2 emissions (from production and transportation) is 257.63 tons/year which forces no emissions penalty cost ($0 for EC_3; no penalty). The total required number of trucks per year is 14 ($\eta d/q$), with $\eta = 2$ trucks per shipment and a batch size of 150 units, computed from Eq. (4.18). The optimal policy was not affected by introducing the penalty chart in Table 4.1; however, TC_1 was increased to $48351.44, where SC_1, EC_1, EC_2, EC_3, and EC_4 represent, respectively, 49%, 8%, ~0%, 0%, and 43% of $48351.44. For this Scenario, $\eta = 2$, $\lambda = 2$, $P = 2177$, and $q = 153$, where $E + E_{tr} = 219.99 < 220$. So, when emissions penalty are included, the system is optimised such to avoid incurring penalty from exceeding carbon emissions limit.

***Table 4.2**. A sample search for the optimal solution.*

η	λ	P	q	TC_1	$\eta t_c - q \geq 0$	Value 1	Value 2
1	8	2285	73.17	50431.25	6.83	50431.25	
1	7	2303	77.54	49438.78	2.46	49438.78	49438.78
1	6	2277	83.33	48441.93	-3.33	Infeasible	
2	4	2335	115.94	50296.32	44.06	49438.78	50296.32
2	3	2364	129.57	49000.74	30.43	49000.74	49000.74
2	2	2396	151.17	48002.44	8.83	48002.44	48002.44
2	1	2433	196.80	48448.80	-36.80	Infeasible	
3	3	2346	145.32	52006.46	94.68	48002.44	52006.46

η	λ	P	q	TC_1	$\eta t_c - q \geq 0$	Value 1	Value 2
3	2	2384	167.54	50588.21	72.46	48002.44	50588.21
3	1	2427	212.96	50468.29	27.04	48002.44	50468.29

For example, for $\eta = 1$, $\lambda_{max} = \frac{1}{\eta t_c}\sqrt{\frac{2S_m d}{h_m(1-d/P_{min})}} = \frac{1}{1\times 80}\sqrt{\frac{2\times 1200\times 1000}{60\times(1-1000/1100)}} = 8.29$ or 8.

Environmentally, and from a cost perspective, it is best to focus on reducing energy costs to seek alternative cheaper and greener sources of energy. The system has been optimized for various production rates (from the minimum 1100 units/year to the maximum permissible 3000 units/year) as shown in Fig. 4.4.

From Fig. 4.4, it can be observed that there is a wide range for P ($1850 < P < 2650$) where the total cost TC_1 remained under \$50,000, or 3% or above the optimal value of $TC_1 = \$48351.44$. This provides great flexibility for production planning personnel to adjust operations to accommodate situations as they may arise on the production floor. Significant increases or drops in the total system costs are attributed to the CO_2 emission penalty costs, which can be avoided if operating at production rates that are not too low (<1800) or too high (>2600).

As P increases, λ reduces gradually (from 5 ($1100 \leq P \leq 1200$) to 3 ($1200 < P \leq 1700$) to 2 ($1700 < P \leq 3000$)). The batch size in general decreases as P increases; however, with every drop in λ there is a significant increase in the batch size. The batch size varies between 140 and 160 which does not result in any change in the number of trucks per shipment (fixed at 3 trucks) and consequently the number of trucks per year at higher production rates (lower λ) is lower. This leads to a reduction in CO_2 emissions from transport as the production rate of the facility increases.

The cost of CO_2 emissions from production showed that operating at lower or higher production rates increases CO_2 emissions and additional costs, as per Eq. (4.3). The amount of CO_2 emissions from production was found to be much more than that of transport and thus the behaviour of the CO_2 emissions penalty is mainly driven by CO_2 emissions from production. Energy was also investigated for the different production rates. As the production rate of the facility is increased, the associated energy usage reduced, from Eq. (4.15), consequently reducing associated costs.

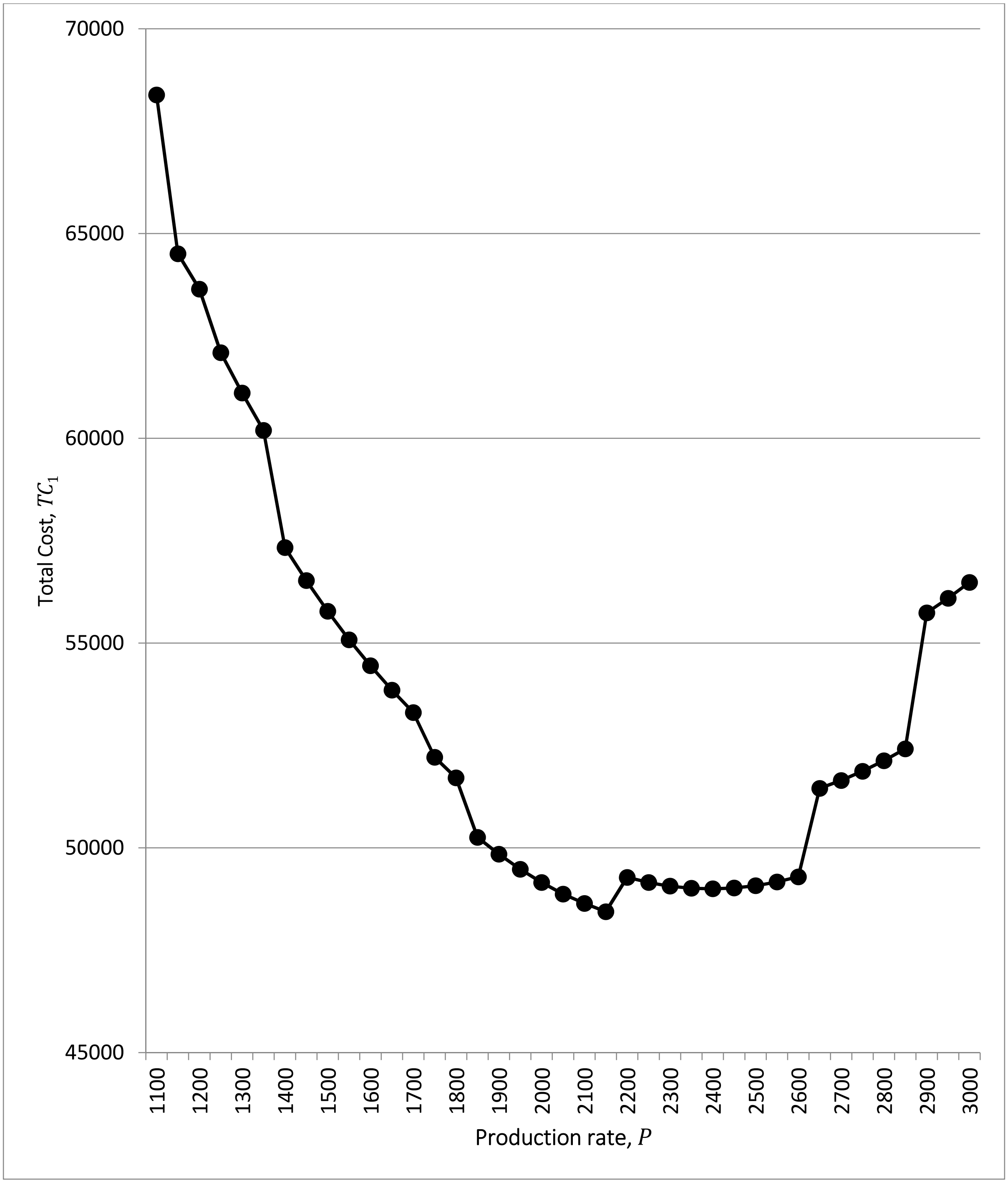

Figure 4.4. *The behaviour of the total cost for different production rates (classical coordination)*

The supply chain (financial and transportation) costs have also been plotted for the different production rates. As the production rate of the system increases the supply chain costs increase. Considering supply chain costs alone, the results suggest that it is best to operate at lower production rates to reduce financial costs. This is contradictory to the results from EC_2 (transport emissions), EC_4 (energy) where it is more beneficiary to operate at production rates that reduce emissions and energy use and their associated costs, as well as EC_1 (production emissions), which seeks to avoid operating at relatively higher or lower production rates.

The above discussion leads to considering of what if the current model was only optimized for supply chain (financial and transportation) costs only, i.e. SC_1, as this may be the current case for most decision makers. This has been performed, and the optimal scenario obtained is: $P = 1100$, $\eta = 2$ and $\lambda = 7$ with an annual total cost of $TC_1 = \$68772.34$. After including the associated environmental impact with this coordination policy, a summary of the cost distribution is: $SC_1 = \$18750.58$ (27%), $EC_1 = \$7974.00$ (12%), $EC_2 = \$190.59$ (~0%), $EC_3 = \$6,000$ (9%), and $EC_4 = 35,857.16$ (52%) per year. By comparing these results with those when TC_1 in Eq. (4.19) is optimised, the supply chain cost alone is \$5,243.16 cheaper, but the overall total system cost is higher by \$20420.90. That is, there is approximately 25.56% savings in the total system costs per year when considering CO_2 emission costs and energy costs in the optimization process. The annual energy cost associated with the optimal production scenario for SC_1 alone is significantly larger (43% vs. 52%) and an annual CO_2 emission costs (\$7974 + \$190.59 + \$6,000) account for 21% (increased from 9%); however, the supply chain costs only account for 27% of the total costs (reduced from 49%). There is a total of 453.59 tons/year of CO_2 emissions, which is 257.63 tons of CO_2 emissions more per year (an increase in both emissions from production and transport). This increase in CO_2 emissions forces a third level emissions penalty. The batch size is $q = 146$ units, with $\eta = 2$ trucks per shipment and 14 trucks per year.

Comparing both scenarios, it is clear that implementing the model (optimizing energy and emissions costs) exhibits a significant reduction in CO_2 emissions and their associated costs, as well as a significant reduction in energy costs showing that being environmentally responsible could actually be financially beneficial for the overall total costs of a supply chain. In both scenarios, the CO_2 emissions from production are significantly larger than the CO_2 emissions from transport, which implies that investment in green manufacturing/production facilities will have a significant impact over investment in green transportation modes given that the costs of investments are indifferent. This observation may not be the case for the situation where the distance travelled between the manufacturer and retailer is significantly longer (this model instance assumes a travelling distance of 300 miles). In general, including the associated energy and CO_2 emissions costs tend to push production to a faster speed such that more is shipped per truck and fewer trips are made.

4.8.2.1 Energy effect of equipment technology

Dahmus and Gutowski (2004) showed that depending on the type of the machine the machining energy breakdown can be classified into two main components as illustrated in Fig. 4.5. A fixed component representing the idle energy consumed when operating the machine and a variable component that represents the energy required for the machining operations that are a function of the metal removal rate (equivalent to the production rate). For the case of this study, the same machine (same Kilowatt hour rate) is tested at various energy breakdowns that can correspond to different machines presented in Dahmus and Gutowski (2004). Here, three energy cases A, B and C, hypothetically representing three different machines, are considered with their input parameters listed in Table 4.3. For example, Case B can refer to a machining center that is part of an automated line with numerous auxiliary equipment which account for the large fixed energy breakdown percentage indicating that 70% of energy is being used whether or not a part is being produced. Case A and Case C may refer to similar machines of different age where Case C is the older aged machine; the constant energy requirements of a machine become larger as a machine is older (Dahmus and Gutowski, 2004).

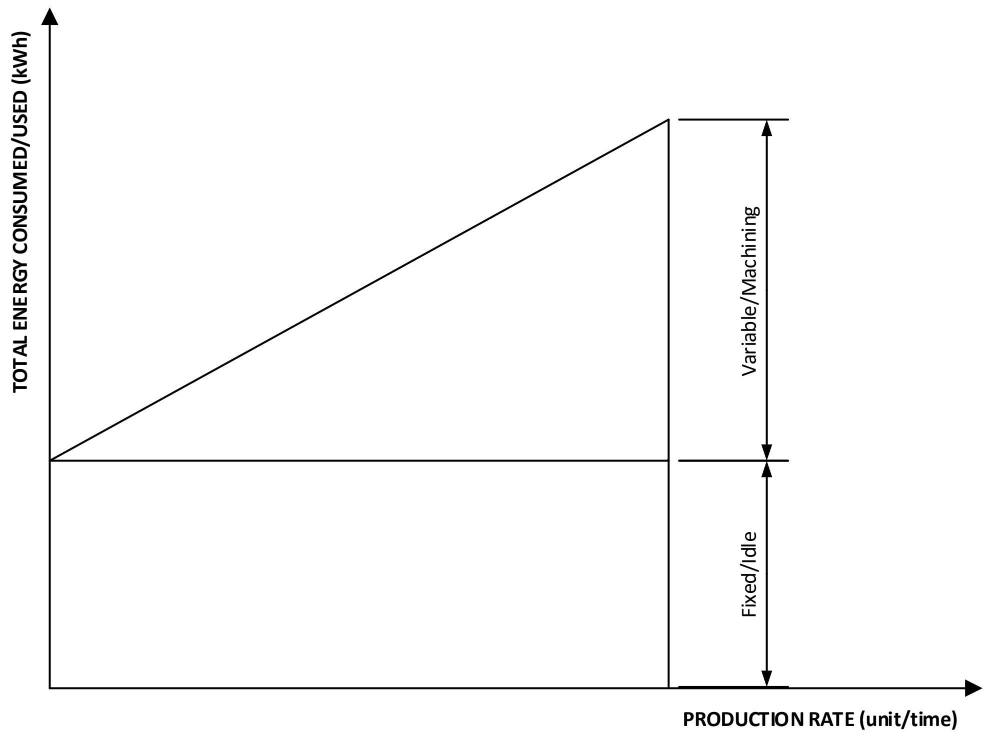

Fig 4.5. *The behaviour of total energy consumed/used for increasing values of the production rate.*

Table 4.3. *The fixed and variable energy components for the three cases considered.*

	CASE A	**CASE B**	**CASE C**
Fixed energy percentage breakdown	15%	70%	50%
Variable energy percentage breakdown	85%	30%	50%
C_0' (in KWh/unit)	57.96	270.47	193.20
C_1' (in KWh/year)	361,275	127,509	212,516

The developed models have been applied for each machine (energy) configuration. In all energy breakdown cases, the energy consumed/used decreases as the production rate increases. As the percentage of the variable component increases the reduction in energy becomes more prevalent, showing that investment in equipment that has a smaller fixed energy component in the energy breakdown can be considered more environmentally friendly when operating at higher production rates. Such equipment may require an initial investment, which can be justified by the savings from energy costs attained, especially, if operating at higher production rates.

Fig. 4.6 illustrates the general behaviour of the model's total cost function, TC_1, is similar for the three energy breakdown cases, however, the cases where the energy breakdown is more heavily weighted towards the variable component the savings in the total system costs are more realized. This is more evident at higher production rates. That is, (1) Case A, $1850 < P < 2650$, total system cost that is less than 3.5% ($< \$50{,}000$) of the optimal total system cost ($TC_1 = \$48{,}351.44$), (2) Case B, $1850 < P < 2450$, total system cost ($TC_1 = \$58012.94$) is less than 3.5% ($< \$60{,}000$), and (3) Case C, $1800 < P < 2500$, total system cost ($TC_1 = \$54560.47$) is less than 2.6% ($< \$56{,}000$). This suggests that the less sensitive TC_1 is for a range of P (around the optimal value) the more flexibility an operation manages has in selecting the P value that he/she find reasonable. It was shown that the lower the fixed energy percentage is the lower is the total cost. It can also be concluded that for equipment with low idle energy use and operating them at higher production rates is more energy efficient, have total system costs that are less sensitive to production variances near the optimal production rate, and thus more cost effective for the overall supply chain.

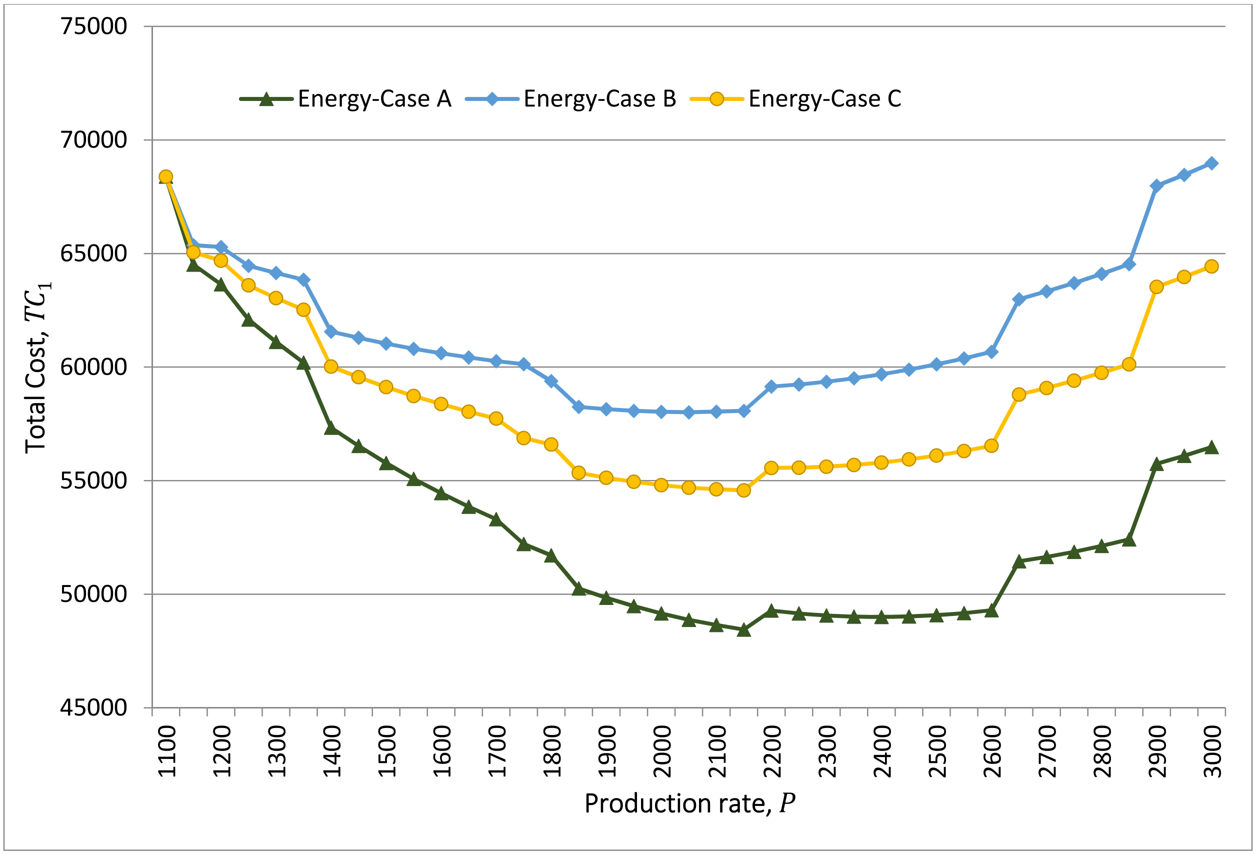

Fig 4.6. *The behaviour of the total cost for different production rates for the three energy cases with classical coordination*

4.8.2.2 Effect of truck capacity

Truck capacity can play a major role in determining the amount of CO_2 emissions from transport as a result of more or less trucks per year that are required to deliver products. The truck capacity initially assumed was 80. The model has been repeatedly solved for truck capacities of 40, 80, 120, and 160. The behaviour of the total cost, TC_1, for different truck capacities is shown in Fig. 4.7.

The models, in general, have a similar behaviour; however, the higher the truck capacity, the lower the total cost of operating the supply chain is. For the case when truck capacity $t_c \leq 160$ the exact parameters were observed for EC_2, TC, q, λ, number of trucks per year, number of trucks per trip, etc. Accordingly, it can be concluded that when the truck capacity is large enough, such that any batch size is always less than the truck capacity, the total cost model will exactly be the same regardless of the truck capacity. For the case of this example, the fuel consumption of the trucks was assumed to be constant. However, it should be noted that trucks of different capacities (different sizes or classes) do have different fuel consumptions, and different CO_2 emission contributions. This is more prevalent if one considers different fuel types (diesel, hybrid, etc.) or various engine configurations and truck manufacturers (Gurtu et al., 2015). Further, the weight of the truck (that is if a truck is at full capacity, partially empty, or empty) will also have an effect on both fuel consumption and the CO_2 emissions contribution. Subsequently determining the type of vehicle fleet used, the number of trucks, and the different combinations of truck sizes that may be used to satisfy the shipment demand and inventory policy that minimizes costs, fuel and GHG emissions are questions that should be considered and answered. This is an appealing investigation that requires revisiting the developed model and is left for future work.

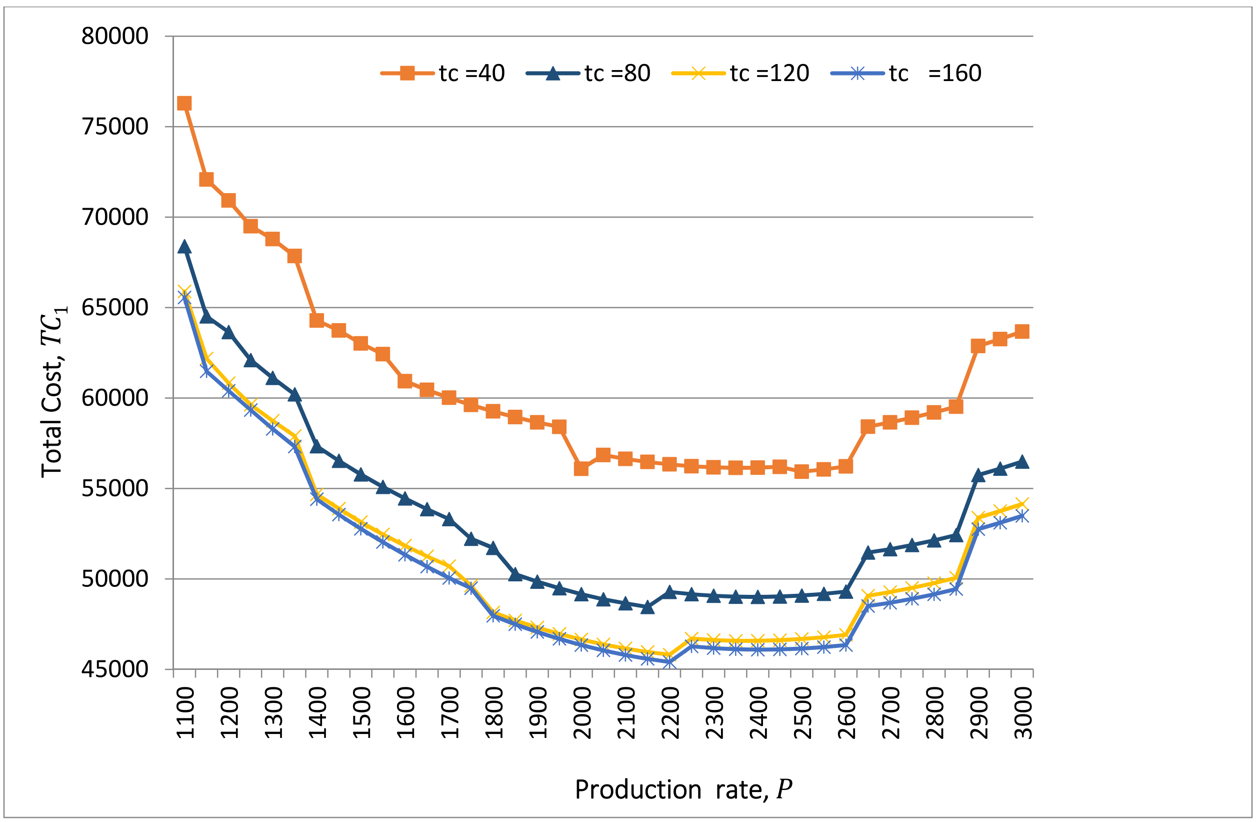

Fig. 4.7. *The behaviour of the total cost for different production rates and truck capacity.*

4.8.2.3 Effect of holding cost

The inventory holding cost is a primary driver that affects inventory decisions throughout a supply chain. For example, low inventory costs may incline the manufacturer to produce large batches, or high inventory costs may push for smaller batches to reduce inventory and hence overall holding costs. Warehouse location, type of equipment technology used for storage and material handling, access to capital and insurance are all factors that may contribute to inventory holding costs (Waters, 2003). The holding cost ratio (manufacturer to retailer holding costs) is investigated and the behaviour of the total cost for the Base Model I is shown in Fig. 4.8. As the holding cost of the manufacturer increases (while keeping the holding cost of the retailer fixed at a value) the total cost of the system increases, concluding that having lower manufacturer holding costs is beneficiary. Supply chain costs are increased when operating at high manufacturing holding costs. However, as the production rate is higher, the difference in supply chain costs between lower and higher manufacturing holding costs is also increased making it important to have low manufacturing holding costs if the system seeks to operate at higher production rates. Notably, it is observed that EC_2 is higher when the manufacturer holding costs are decreased for some production rates. This implies that even though total system costs are reduced with lower manufacturer holding cost, we do have a trade-off against the amount of CO_2 emitted from transportation in some cases.

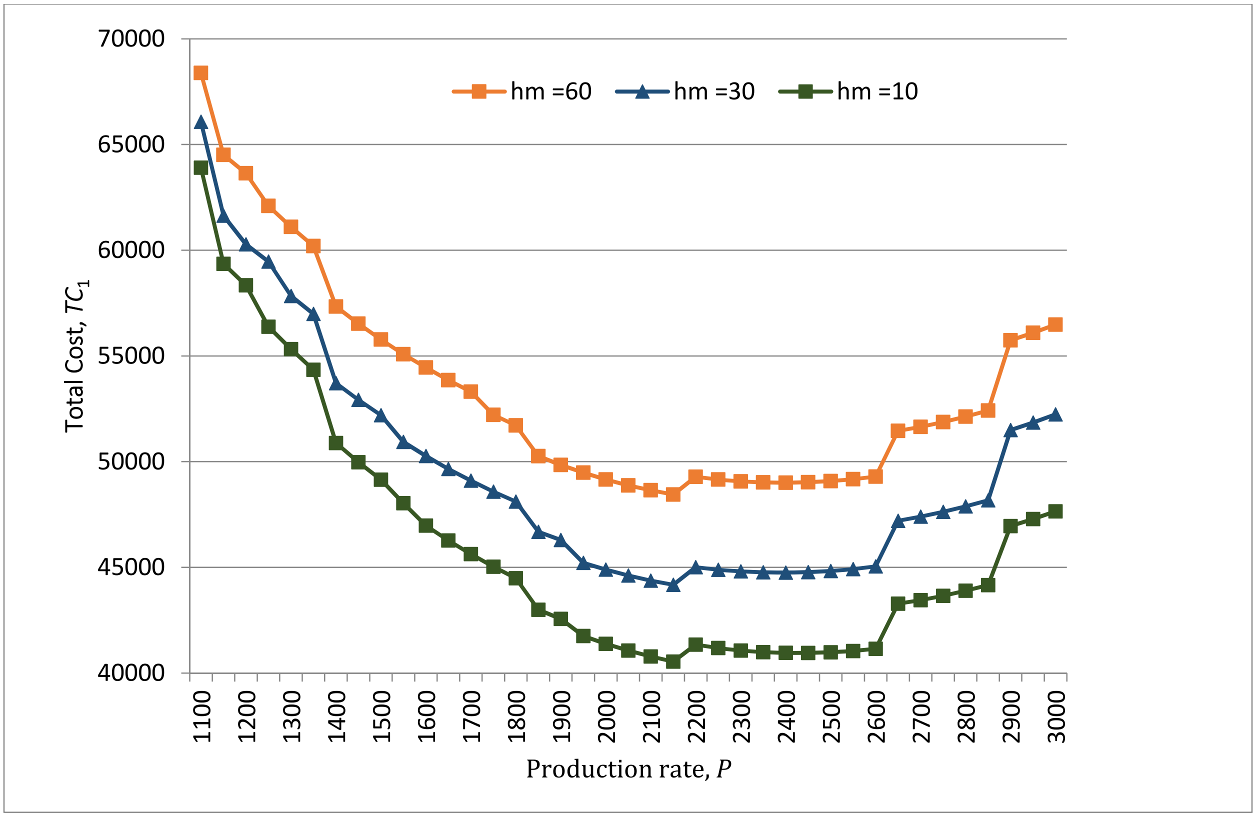

Fig 4.8. *The behaviour of the total cost for different production rates and manufacturer holding cost.*

4.8.2.4 Effect of setup cost

Similarly to inventory holding costs, the production setup cost or fixed ordering cost associated with placing an order affects the inventory policy through economies of scale. The setup cost ratio (manufacturer setup to retailer fixed ordering costs) is investigated and the results are presented in Fig. 4.9. For low manufacturer setup cost (with respect to retailer fixed order cost) the total system costs are low and the variance in production rates for which the system can operate at ‘‘near’’ optimal is larger. It was found that there is no change/effect in the values of EC_1 or EC_4. For low manufacturer setup costs, the supply chain costs are eventually low. The difference in SC_1 values between operating with low manufacturer setups costs and high manufacturer setup costs is increased at high production rates, indicating that keeping low manufacturing setup costs is very beneficial when operating at high production rates.

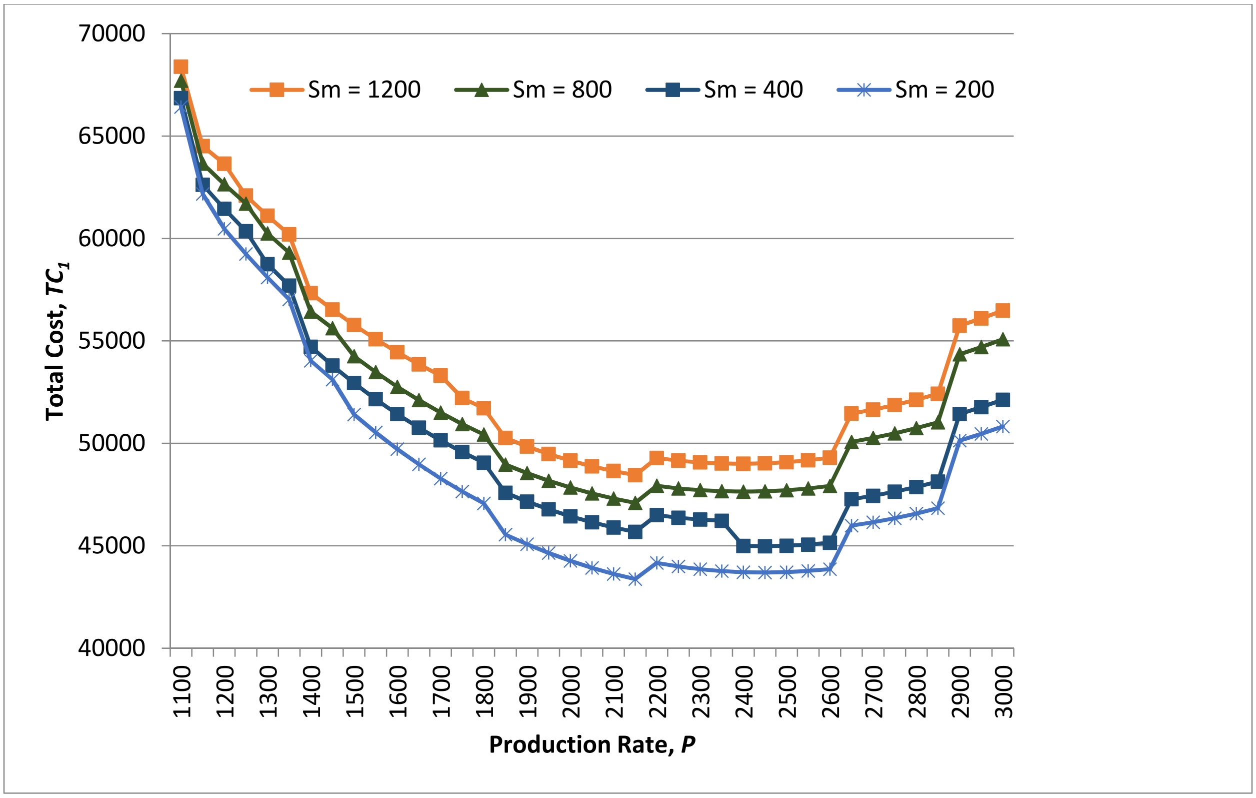

Fig 4.9*. The behaviour of the total cost for different production rates and manufacturer setup cost.*

4.8.3 The VMI-CS model

In order to keep a fair comparison with the classical coordination model, the following values have been assumed as per Zanoni et al. (2014a):

$h_m^{fin} = 5$ (\$/unit/year);

$h_m^{ph} = 55$ (\$/unit/year);

$h_r^{fin} = 10$ (\$/unit/year);

$h_r^{ph} = 20$ (\$/unit/year).

The optimal solution of Eq. (4.19) for the same input parameters used for the classical case gives: $P = 2509$ and $\lambda = 3$, with a total cost of $TC_2 = \$42705.51$. The percentage distribution of costs is: $SC_2 = \$17774.77$ (42%), $EC_1 = \$4999.04$ (12%), $EC_2 = \$190.59$ (~0%), $EC_3 = \$1{,}000$ (2%) and $EC_4 = \$18{,}741.11$ (44%). Total CO_2 emissions from the system are: 297.099 tons per year (79.3 tons/year more than classical coordination). The batch size, $q = 225.04$ units, with $\eta = 3$ truck per shipment and 14 trucks per year. Comparing the results with those of the classical case ($TC_1 = \$48351.44$), we observed the following: $SC_1 \downarrow (-5838.0)$, $EC_1 \uparrow (1229.0)$, $EC_2 - (0)$, $EC_3 \uparrow (1000)$, and $EC_4 \downarrow (-2037.8)$.

Fig. 4.10 shows the behaviour of the total cost functions for Base Models I and II, i.e. TC_1 and TC_2 from Eqs. (4.17) and (4.19), respectively, for different production rates and the default values of the input parameters assumed for the example in Fig. 4.4. The results show that the VMI-CS policy, Base Model II, has lower costs than the classical model for $1100 \leq P \leq 3000$. The savings ($\Delta TC = TC_1 - TC_2$) from adopting the VMI-CS policy increases as P increases ($\Delta TC = 1886.9P^{0.36}$, where $R^2 = 0.9727$, using Excel best-fit tool).

The same comparison has been applied to energy Cases B and C in Table 4.3 to study the effect of various energy configurations of the optimal policy and the environmental components and the behaviour was found to be very similar. The optimal policies for the classical and VMI-CS models for the three energy cases of Table 4.3 are summarised in Table 4.4. Similar to Case A, VMI-CS model reported savings for Cases B and C for $1100 \leq P \leq 3000$ (Case B: $\Delta TC = 1894.1P^{0.3596}$, where $R^2 = 0.9701$; Case C: $\Delta TC = 1886.1P^{0.3601}$, where $R^2 = 0.9715$).

Similar to the classical model, as the production rate increases, the benefit of using a machine with lower idle energy usage becomes more important. The manufacturer holding costs (physical holding cost), setup costs and the truck capacities were also varied for the VMI-CS policy agreement model and the system behavior was found to be similar to that of the classical model. Noticeable in all VMI-CS examples, it was shown that even though optimal production rates yield lower total costs than those obtained from the classical coordination models, the higher the production rate, the more significant the total system cost savings.

Table 4.4*. Optimal policies for the VMI-CS and classical modes for the three energy consumption/usage cases.*

Energy Case	Model	η	λ	q	P^*	$SC_{1,2}$	EC_1	EC_2	EC_3	EC_4	$TC_{1,2}$
A	VMI-CS	3	3	225.03	2509	17774.77	4999.04	190.59	1000	18741.11	42705.51
	Classical	2	2	152.46	2177	23612.75	3769.18	190.59	0	20778.93	48351.44
B	VMI-CS	3	3	224.18	2177	17843.04	3769.18	190.59	0	30535.00	52337.80
	Classical	2	2	154.07	2057	23366.33	3617.545	176.98	0	30852.09	58012.94
C	VMI-CS	3	3	224.18	2177	17843.04	3769.18	190.59	0	26987.96	48790.78
	Classical	2	2	152.46	2177	23612.75	3769.177	190.59	0	26987.96	54560.47

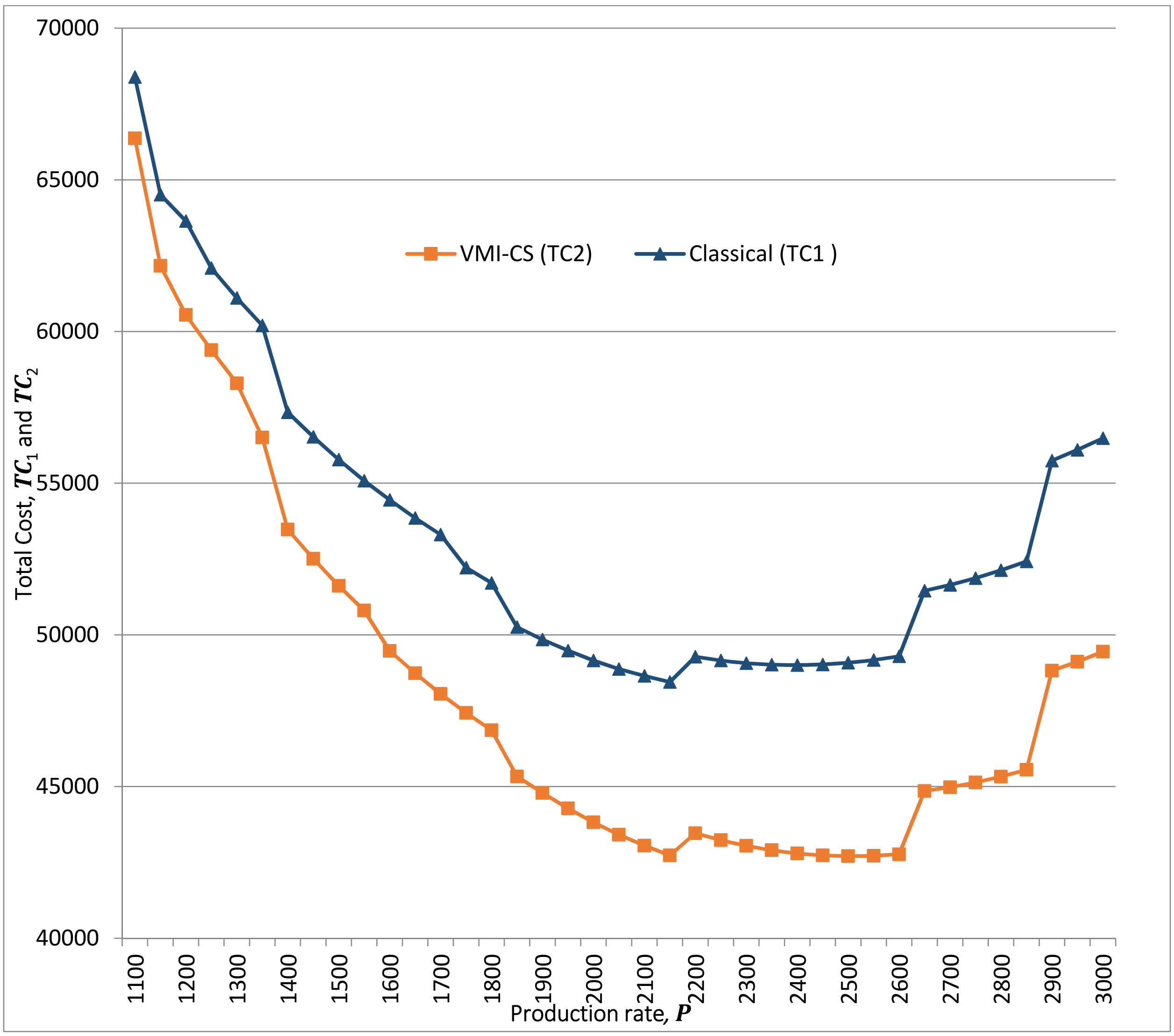

Fig. 4.10. *The behaviour of the total costs for Base Models I and II for different production rates.*

We have run a comparison between the VMI-CS and the classical model for varying truck capacities, $t_c = 80$ (base case in Table 4.4), 160, 240 and 320, for energy Case A above (as it reported the lowest costs). The results showed that $\Delta TC = TC_1 - TC_2$ increased (from 5645.93 to 6605.57 to 7441.83 and stayed at that level), mainly because less trucks per year were used and different q, λ and P values were reported. The difference in supply chain costs for the two models, $SC_1 - SC_2$, increased as t_c increased (from 5837.97 to 6565.19 to 7326.74 and remained unchanged for increase in capacity beyond 320). Savings in cost of emissions from production, EC_1, when adopting a VMI-CS policy instead of a classical coordination, decreased from 1229.86 for $t_c = 80$ to less than 100 for other values of t_c. Similar results were reported for energy costs, EC_4, where savings decreased from 2037.82 to less than 100. The reason for this behaviour is that as t_c increased, the difference in the optimal production rates for the two models reduced to almost a negligible value.

4.9 Summary and conclusions

This paper presented two models considering greenhouse gases (mainly, CO_2) emissions from the production and transportation operations between a single vendor (manufacturer) and single buyer (retailer) with applicable multi-level emission taxes and required energy usage for production. Two models were selected from the literature and modified to account for emissions from transportation and emissions from the production process with the consideration of truck capacity. The first model employs a classical coordination policy (Base Model I) as presented in Jaber et al. (2013), and the second employs a VMI-CS policy (Base Model II) as presented in Zanoni et al. (2014a).

The results showed that the optimal production scenarios for VMI-CS allow the system to operate more economically. Energy was found to be the main environmental cost component for both models, and targeting a reduction in energy usage is a priority. Not only to reduce costs, but also to account for environmental impact associated with acquiring energy, especially if from a non-renewable sources (coal, fossil fuels, etc.). Further results showed that obtaining equipment that is low on idle energy usage will benefit the system by shifting the optimal production rates to higher values. This becomes very advantageous if the facility/equipment is producing more than one product as it allows the system to satisfy demand faster and become available for other products. Other results showed that reducing the holding and setup costs at the manufacturer side benefited the system in terms of total system costs. Savings could also be achieved by using transportation trucks with higher capacities. However, beyond a certain truck capacity the benefits from using larger trucks became insignificant as trucks travel with vacant cargo space. It should be noted that not all production policies provide a win–win situation with regard to cost savings and environmental impact. For example, a VMI-CS optimal policy may reduce overall system and energy costs, but provide an increase in CO_2 emissions and accordingly their associated costs. Even though the environmental trade-off is in favour of energy savings and the economic trade-off is in favor of both the supply chain and energy costs, a company policy of prioritizing CO_2 emissions reductions may come to a conflict with other objectives. It becomes clear that the prioritization of environmental impacts is required when determining how to best protect the environment.

Overall, this chapter provided an operational perspective to a two-level supply chain model that supports environmentally responsible decision-making process. The chapter is believed to be the first in introducing energy and greenhouse gas emissions from production and transportation together considering different coordination policies. A decision maker in a supply chain may use the suggested models of this chapter to optimize their operations, choose a coordination mechanism/policy, or determine investment opportunities through forecasting improvements in the supply chain's performance through the modification of input parameters. The breakdown of GHG emissions and related costs provides useful information to decision makers as where to focus efforts to reduce costs and the environmental burden of the supply chain. For example, a decision whether replacing diesel trucks with hybrid or electric vehicles, or to upgrade machining equipment can be made by adjusting the parameters that contribute to the relevant processes and thus forecast GHG emissions and potential costs. Further, this research can be considered a stepping-stone to other research works investigating other environmental aspects associated with the acquisition of energy consumed/used in production (e.g. GHG emissions, resource depletion, etc.). Investigating and expanding on this will yield to decisions regarding the type of energy acquired and investments in green/renewable energy sources.

This study has limitations. It neglected the investigation of material(s) used for production, possible scrap from production or scrap from quality issues. The reduction of scrap and manufacturing solid waste are key elements to protecting the environment. Including them in a supply chain context will assist in developing managerial decisions regarding reduction in raw materials or streamlining operations to eliminate waste. Both helping the environment in terms of slowing down the depletion of natural resources; moreover, the energy, emissions and pollution associated with the extraction of the raw materials. This also paves the way to investigate product re-use, material recycling and other options to reduce solid wastes. Such processes do come at a cost and have their environmental impact as well; energy and costs required to collect, dis-assemble and assemble, and recycle at their respective facilities. There are definitely trade-offs in the process and the need to find an optimal policy to achieve maximum environmental benefits at economic costs is vital. Further extensions of this work could include addressing the introduction of a second product to the system, multiple suppliers or buyers, or a combination of both.

Chapter 5

CARBON EMISSIONS AND ENERGY EFFECTS ON MANUFACTURING-REMANUFACTURING INVENTORY MODELS

This chapter presents a reverse logistics manufacturing-remanufacturing inventory model. Elements of this chapter are taken from Bazan et al. (2015b).

5.1. Introduction

In a similar approach to the available reverse logistic mathematical models that are based on the EOQ setting, the fundamental objective is to operate at minimum cost. The underlying difference between the model of this paper and the models surveyed above is that it accounts for the environmental costs of the system, which have been previously ignored.

5.2. Model Concept, Main Assumptions and Nomenclature

The model of Richter (1996a) is the first EOQ based mathematical model to consider the disposal of items and can be considered a base model for this work. The main assumptions considered by Richter (1996a) are that items are deemed as-good-as-new, the recovery process is applicable only to the product as a whole, and that the recovery of returned products is indefinite (i.e., it can be recovered infinite number of times with no deterioration to product quality or material characteristics). The focus of this study is to include environmental implications present in a reverse logistic model. For this reason, the consideration of a limited number of times for which an item can be recovered directly affects the number of returned items that are disposed. This consideration is presented in El Saadany et al. (2013) and for its environmental importance, which is considered in the development of the proposed model in this paper.

The model considered in this chapter is a manufacturer that produces a product and ships it to a market. Used items that are no longer of service to customers are collected from the market and returned to the facility to be remanufactured or disposed. The system considered here consists of two inventory stocks, one for serviceable (new produced and remanufactured) items and the other is for repairable items collected from the market for recovery. Remanufactured items are assumed to be as-good-as-new. The produced/manufacturing and remanufacturing processes are assumed to always be in control with no generation no defective items. The material flow is depicted in Figure 5.1.

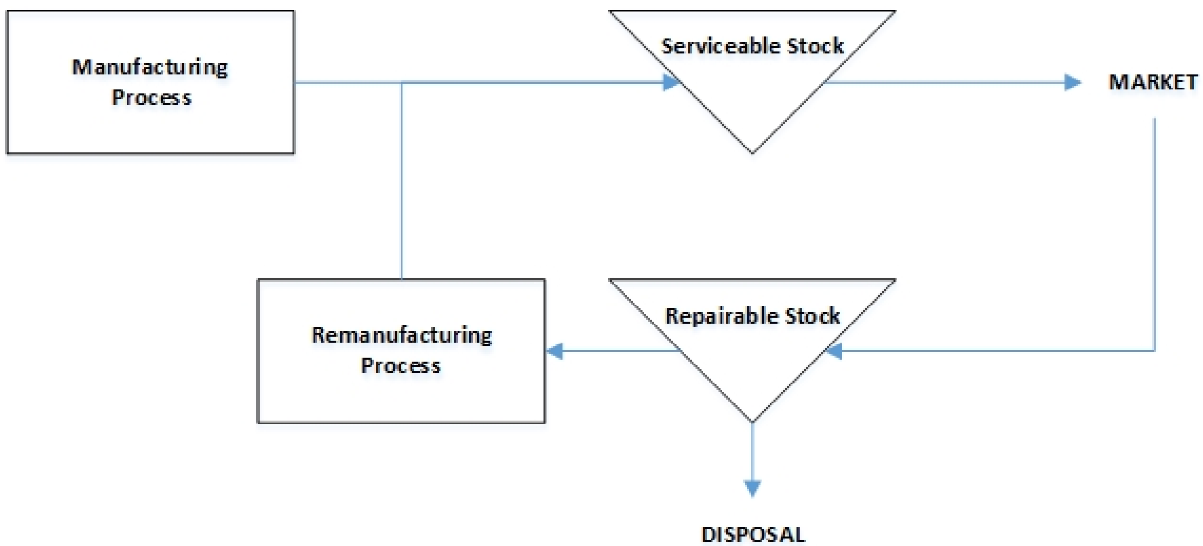

Fig. 5.1 *Material flow of a single item for a single manufacturer-remanufacturer*

In the presented model, the manufacturing and remanufacturing processes are assumed to be comprised primarily of machine tools. The paper assumes land transportation where items in the serviceable stock are shipped to the market by trucks that return to the facility the collected used items from the market. The model also considers energy usage and GHG emissions subject to an emissions penalty tax as per The European Union Emissions Trading System (Jaber et al., 2013). Concisely, the system cost parameters considered in the model are listed below:

1. Holding cost for serviceable stock (both manufactured and remanufactured),
2. Holding cost for repairable stock,
3. Production setup cost (both manufacturing and remanufacturing setup costs),

4. Production unit costs (both manufacturing and remanufacturing unit costs),
5. Remanufacturing investment cost,
6. Cost of waste disposal,
7. Cost of transportation,
8. Cost of GHG emissions from production (both manufacturing and remanufacturing),
9. Cost of GHG emissions from transportation,
10. GHG emissions penalty cost, and
11. Cost of energy used for production (manufacturing and remanufacturing).

The objective of the model is to develop a total cost function that is minimized by determining the following: the number of manufacturing batches per cycle, the number or remanufacturing batches per cycle, and the number of times an item can be remanufactured. Similar to El Saadany et al. (2013) the remanufacturing batch size per cycle is a function of the manufacturing batch size per cycle, the number of manufacturing batches per cycle, and the number or remanufacturing batches per cycle. For ease of understanding, the behavior of both the serviceable and repairable stocks is illustrated in Figure 5.2.

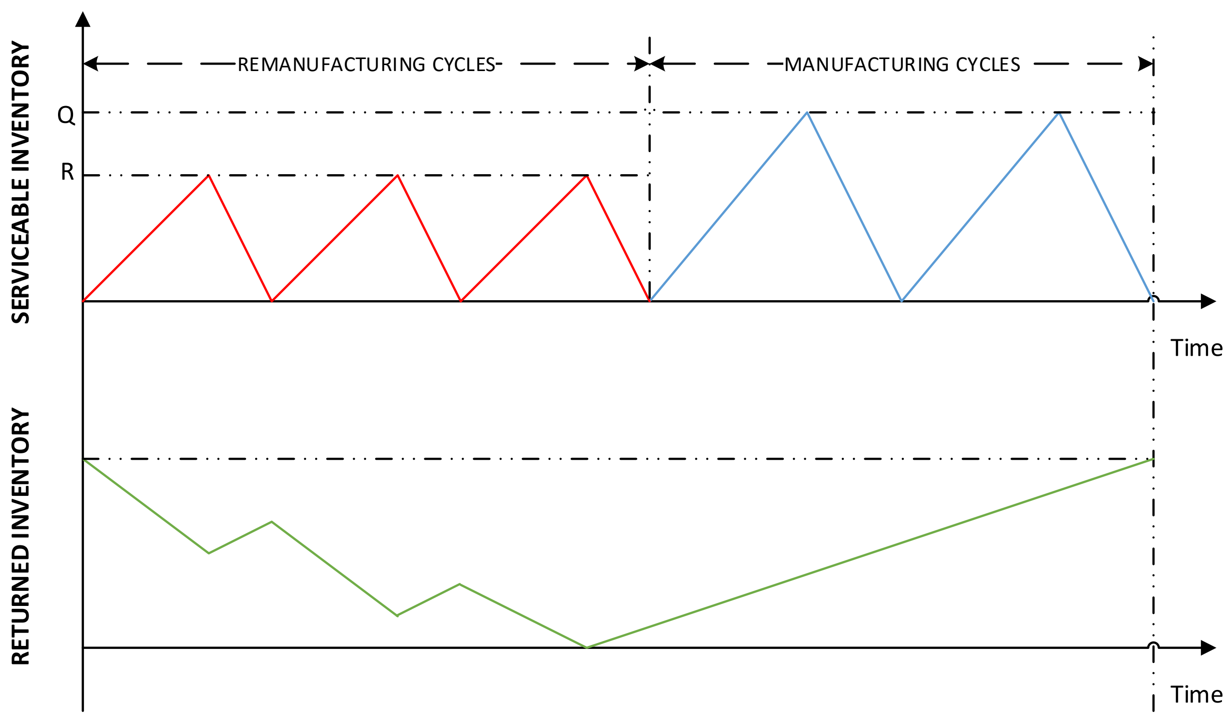

Fig. 5.2 *Inventory of serviceable stock for manufacturing and remanufacturing as well inventory stock of returned items*

A list of the decision variables and other parameters with their notation is listed below:

Decision Variables

n	The number of manufacturing batches per cycle, where $n \geq 1$ and integer
m	The number of remanufacturing batches per cycle, where $m \geq 0$ and integer
ζ	The number of times an item is remanufactured, where $\zeta \geq 0$ and integer

Input and Other Parameters

β	The nominal proportion of items returned for remanufacturing when an item is remanufactured for an unlimited number of times, where $0 \leq \beta \leq 1$
β_ζ	The actual proportion of items returned for recovery purposes when an item is recovered for a limited ζ number of times, where $\beta_\zeta = 1 - \left[\frac{(1-\beta)}{(1-\beta^{\zeta+1})}\right]$
Q	The manufacturing batch size per cycle [units]
R	The remanufacturing batch size per cycle [units], where $R = \frac{\beta_\zeta nQ}{(1-\beta_\zeta)m}$, [units]
T	Cycle time (interval length), where $T = \frac{nQ+mR}{d}$, [year]
d	The demand rate (deterministic and constant), [units/year]
γ	The manufacturing rate, where $\gamma > d$, [units/year]
ν	The remanufacturing rate, where $\nu > d$, [units/year]
h_p	The holding cost for a manufactured unit of the serviceable stock, [$/unit/year]
h_r	The holding cost for a remanufactured unit of the serviceable stock, where $h_p \neq h_r$, [$/unit/year]
h_u	The holding cost for a returned unit of the repairable stock, where $h_p > h_u$ and $h_r > h_u$, [$/unit/year]
S_m	The setup cost per manufacturing run/batch, [$]
S_r	The setup cost per remanufacturing run/batch, [$]
c_{mr}	The cost to manufacture one unit, [$/unit]
c_{re}	The cost to remanufacture one unit, [$/unit]

c_{inv} The annual investment in the design process of the product to, theoretically, be able to remanufacture it for an indefinite number of times, [$/year]

θ The investment increment factor that governs the ratio of investment for each remanufactured generation, where $0 \leq \theta < 1$

c_w The cost to dispose one unit, [$/unit]

F_t The fixed cost per truck per trip, [$/truck]

t_c The truck capacity, [units/truck]

t_k The number of trucks required per year, where $t_k = d/t_c$, [trucks]

c_t The variable cost per unit transported per distance travelled, [$/unit]

c_{ec} The carbon emissions tax per ton of GHG emissions, [$/ton]

a_p An emissions function parameter for manufacturing, [ton.year^2/unit^3]

b_p An emissions function parameter for manufacturing, [ton.year/unit^2]

c_p An emissions function parameter for manufacturing, [ton/unit]

a_r An emissions function parameter for remanufacturing, [ton.year^2/unit^3]

b_r An emissions function parameter for remanufacturing, [ton.year/unit^2]

c_r An emissions function parameter for remanufacturing, [ton/unit]

g_t The number of gallons per truck per distance travelled, [gallons/truck]

e_t The amount of GHG emissions from one gallon of diesel-truck fuel, [ton/gallon]

C_0' The coefficient of the inverse model (the required energy at the machine to manufacture one unit), [kWh/unit]

C_1' The coefficient of the predictor (the required energy per year when manufacturing is idle), [KWh/year]

C_0'' The coefficient of the inverse model (the required energy at the machine to remanufacture one unit), [kWh/unit]

C_1'' The coefficient of the predictor (the required energy per year when remanufacturing is idle), [KWh/year]

c_{en} Cost of energy [$/KWh]

The development of the cost functions are presented in Section 5.3.

5.3 Cost Functions

From Figure 5.2, the annual holding cost of serviceable stock is given as:

$$H_1 = H_1(n,m,\zeta) = \frac{h_p\left(\frac{nQ^2}{2d} - \frac{n^2Q^2}{2\gamma} + \frac{Q^2}{2\gamma}n(n-1)\right) + h_r\left(\frac{mR^2}{2d} - \frac{m^2R^2}{2\nu} + \frac{R^2}{2\nu}m(m-1)\right)}{T}$$

$$= \frac{Q}{2(1-\beta^{\zeta+1})}\left[h_p(1-\beta)\left(1-\frac{d}{\gamma}\right) + h_r\frac{n}{m}\frac{\left(\beta-\beta^{\zeta+1}\right)^2}{(1-\beta)}\left(1-\frac{d}{\nu}\right)\right] \tag{5.1}$$

Also, from Figure 5.2, the annual holding cost of repairable stock is given as:

$$H_2 = H_2(n,m,\zeta) = \frac{h_u\left\{\frac{mR^2}{2\nu} + \frac{m(m-1)R^2}{2d} + \frac{\beta}{2d}(mR+nQ) - \frac{n\beta Q}{1-\beta}\left((m-1)\frac{R}{d} + \frac{R}{\nu}\right)\right\}}{T}$$

$$= h_u\frac{nQ}{2}\left(\frac{\beta-\beta^{\zeta+1}}{1-\beta}\right)\left[\left(\frac{\beta-\beta^{\zeta+1}}{1-\beta^{\zeta+1}}\right)\frac{1}{m}\left(1-m-\frac{d}{\nu}\right)+1\right] \tag{5.2}$$

The derivations of the above equations are provided in Appendix G.

The annual production setup cost is the sum of the setup costs for all manufacturing and remanufacturing runs per cycle divided by the cycle time, $T = \frac{nQ+mR}{d}$ where $= \frac{\beta_\zeta nQ}{(1-\beta_\zeta)m}$, which is given as:

$$S = S(n,m,\zeta) = \frac{mS_r + nS_m}{T} = \frac{d}{nQ}\frac{(1-\beta)}{(1-\beta^{\zeta+1})}(mS_r + nS_m) \tag{5.3}$$

The annual production cost is the variable production cost per unit for all manufactured and remanufactured items per cycle divided by the cycle time, which is given as:

$$C_p = C_p(\zeta) = \frac{c_{mr}nQ + c_{re}mR}{T} = \frac{d}{(1-\beta^{\zeta+1})}\left[c_{mr}(1-\beta) + c_{re}\left(\beta-\beta^{\zeta+1}\right)\right] \tag{5.4}$$

According to El Saadany et al. (2013), the annual investment in the design process is given as:

$$C_{inv}(\zeta) = c_{inv}\left(1-e^{-\theta\zeta}\right) \tag{5.5}$$

Also, as per El Saadany et al. (2013), the annual cost of waste disposal is given as:

$$C_w = C_w(\zeta) = c_w d\left(1-\beta_\zeta\right) = c_w d\frac{(1-\beta)}{(1-\beta^{\zeta+1})} \tag{5.6}$$

From Bozorgi et al. (2014) and Appendix A.1 in Bonney and Jaber (2011), the annual transportation cost can be assigned as a fixed cost and a variable component cost. For simplification, the transportation cost in this paper is a fixed cost per trip for a round trip (delivers and collects) and is given as:

$$C_t = C_t(\zeta) = \frac{\left(\frac{nQ}{t_c}+\frac{mR}{t_c}\right)F_t}{T} + \frac{\beta_\zeta}{t_c}F_t = \frac{dF_t}{t_c}\left(1+\frac{\beta-\beta^{\zeta+1}}{1-\beta^{\zeta+1}}\right) \quad (5.7)$$

Jaber et al. (2013) show the relationship for GHG emissions based on Bogaschewsky (1995) that has also been verified empirically for machine tools in Narita (2012). A similar relationship can be used for the remanufacturing process and therefore the cost of GHG emissions can be given as:

$$C_{GHGe} = C_{GHGe}(\zeta) = \left(a_p\gamma^2 - b_p\gamma + c_p\right)\left[\left(1-\beta_\eta\right)d\right]c_{ec} + \left(a_r\nu^2 - b_r\nu + c_r\right)\left[\beta_\eta d\right]c_{ec}$$
$$= c_{ec}\frac{d}{\left(1-\beta^{\zeta+1}\right)}\left[(1-\beta)\left(a_p\gamma^2 - b_p\gamma + c_p\right) + \left(\beta-\beta^{\zeta+1}\right)\left(a_r\nu^2 - b_r\nu + c_r\right)\right] \quad (5.8)$$

From the Appendix A.1 in Bonney and Jaber (2011), the annual GHG emissions cost from transportation is given in terms of the amount of GHG emissions emitted from using a gallon of fuel. For the case of this research, the fuel used is diesel for trucks with an average consumption 4mpg travelling a distance of 300 miles between the market and the production facility. Accordingly, the annual cost of GHG emissions from transportation is estimated as:

$$C_{GHGt} = \left[\frac{d}{t_c} + \frac{d\beta_\zeta}{t_c}\right]g_t e_t c_{ec} = \left[\frac{d}{t_c}\left(1+\frac{\beta-\beta^{\zeta+1}}{1-\beta^{\zeta+1}}\right)\right]g_t e_t c_{ec} \quad (5.9)$$

An emissions penalty scheme that penalizes the system for exceeding various permissible emission levels is presented in Jaber et al. (2013) and given as:

$$C_{GHGp} = \sum_{i=1}^{n} Y_i c_{ep,i} \quad (5.10)$$

Li and Kara (2011) present a relationship between the energy used by a machine tool for processing and the number of units processed in terms of material removal rate in cm^3 per second. A similar relationship is found in Zanoni et al. (2014b) in terms of kg material per hour for a continuous production batch. Adjusting the parameters from Li and Kara (2011) for manufacturing and remanufacturing in terms of units produced per year, the cost of energy used per year can be given as:

$$C_N = C_N(\zeta) = \frac{\left[\left(C_o' + \frac{C_1'}{\gamma}\right) nQ + \left(C_o'' + \frac{C_1''}{\nu}\right) mR\right] c_{en}}{T}$$

$$= \frac{d c_{en}}{(1-\beta^{\zeta+1})}\left[\left(C_o' + \frac{C_1'}{\gamma}\right)(1-\beta) + \left(C_o'' + \frac{C_1''}{\nu}\right)\left(\beta - \beta^{\zeta+1}\right)\right] \quad (5.11)$$

In the literature, to the authors' knowledge, the optimization of reverse logistics models have focused on supply chain costs and ignored the environmentally associated costs excluding that of solid waste disposal (Fleischmann et al., 1997; Richter 1996, Bostel et al., 2005; Dobos and Richter, 2003; 2004, El Saadany and Jaber; 2008; 2010; 2011). The minimization of the sum of these costs is referred to, in this paper, as the traditional approach. In that sense, the model seeks to minimize the sum of the terms $H_1 + H_2 + S + C_p + C_{inv} + C_w + C_t$, i.e. the sum of Eqs. (5.1)-(5.7). This is achieved by searching for $\{n, m, \zeta\}$ where the manufacturing batch size is given by:

$$Q = \sqrt{\frac{C}{A+B}} \quad (5.12)$$

, where: $$C = \frac{d}{n}\frac{(1-\beta)}{(1-\beta^{\zeta+1})}\left(nS_m + mS_r\right) \quad (5.12a)$$

$$A = \frac{1}{2(1-\beta^{\zeta+1})}\left[h_p(1-\beta)\left(1-\frac{d}{\gamma}\right) + h_r \frac{n}{m}\frac{\left(\beta-\beta^{\zeta+1}\right)^2}{(1-\beta)}\left(1-\frac{d}{\nu}\right)\right] \quad (5.12b)$$

$$B = h_u \frac{n}{2}\left(\frac{\beta-\beta^{\zeta+1}}{1-\beta}\right)\left[\left(\frac{\beta-\beta^{\zeta+1}}{1-\beta^{\zeta+1}}\right)\frac{1}{m}\left(1-m-\frac{d}{\nu}\right)+1\right] \quad (5.12c)$$

The optimal manufacturing batch size given in Eq. (12) can be obtained by differentiating the sum of Eqs. (5.1)-(5.7) with respect to Q and then equating the sum of these differentials to zero and solving for Q.

This 'traditional' optimization approach has ignored the environmentally associated costs concerning GHG emissions from manufacturing, remanufacturing and transporting products, as well as the cost of energy usage to manufacture and remanufacture the products. In order to calculate the total cost of the system these costs must be included, i.e. the sum of the cost terms $C_{GHGe} + C_{GHGt} + C_{GHGp} + C_N$ is to be added to the aforementioned summation that was minimized, i.e. the sum of Eqs. (5.8), (5.9), (5.10) and (5.11), respectively.

Contrary to this 'traditional' optimization problem the proposed model in this research seeks to treat all environmental aspects of the reverse logistics inventory model as part of the objective function and that all cost terms be collectively optimized (minimized). In this sense the problem may be re-written as:

$$\min TC\{n, m, \zeta\} = H_1 + H_2 + S + C_p + C_{inv} + C_w + C_t + C_{GHGe} + C_{GHGt} + C_{GHGp} + C_N \tag{5.13}$$

The above cost terms, Eqs. (5.1) - (5.13), hold for the case where at least one remanufacturing batch is present ($m \geq 1$) and the collection of used products from the market is required ($\beta > 0$). For the special case where there is no remanufacturing ($m = 0, R = 0$) and no collection of used products ($\beta = 0$), the problem is reduced to one where the optimization is only a function of $\{n\}$. The individual cost terms, Eqs. (5.1) - (5.11), with the exclusion of C_{GHGp} given by Eq. (5.10), which remains the same, are reduced to the following:

$$H_1 = \frac{Q}{2}\left[h_p\left(1 - \frac{d}{\gamma}\right)\right] \tag{5.14}$$

$$H_2 = 0 \tag{5.15}$$

$$S = \frac{d}{Q}(S_m) \tag{5.16}$$

$$C_p = dc_{mr} \tag{5.17}$$

$$C_{inv} = 0 \tag{5.18}$$

$$C_w = c_w d \tag{5.19}$$

$$C_t = \frac{dF_t}{t_c} \tag{5.20}$$

$$C_{GHGe} = c_{ec} d\left(a_p \gamma^2 - b_p \gamma + c_p\right) \tag{5.21}$$

$$C_{GHGt} = \left(\frac{d}{t_c}\right) g_t e_t c_{ec} \tag{5.22}$$

$$C_N(n) = dc_{en}\left(C_o' + \frac{C_1'}{\gamma}\right) \tag{5.23}$$

where the manufacturing batch size for the 'traditional' is given as:

$$Q = \sqrt{\frac{2dS_m}{h_p\left(1 - \frac{d}{\gamma}\right)}} \tag{5.24}$$

The problem has been modeled in Microsoft Excel with the Solver add-in and enhanced with Visual Basic Macros. The solution is obtained by setting $n = 1$, $m = 0$, and $\zeta = 0$ and then solving for the system cost that is to be minimized (either the traditional approach or the proposed collective optimization). The following steps allow for $m = m + 1$ and $\zeta = \zeta + 1$ and the cost be computed and compared against previous iterations until the minimum system cost is found. Numerical examples are provided in the next Section.

5.4 Numerical Examples and Results

Product candidates for remanufacturing include products such as retreaded tires, heavy-duty and off-road (HDOR) equipment, motor vehicle parts, consumer products, IT products, wholesalers, machinery, aerospace and medical devices (United States International Trade Commission, 2012). Tire remanufacturing (also known as retreading) is the largest remanufacturing sector in the United States with regard to the number of remanufacturing facilities (Boustani et al. 2010). Based on its importance and the availability of data, the numerical examples present will reflect the tire remanufacturing industry, and most of the input parameters are actual figures from the tire retread industry in Canada and its Oil Sands customers in Northern Alberta. Accordingly, the following input parameters have been used in the numerical examples (Table 5.1 and Table 5.2).

Table 5.1 *List of input parameters and their respective values*

Input Parameter	Value	Units	Input Parameter	Value	Units
β	0.67	[%]	a_r	0.000000833	[ton.year^2/unit^3]
d	4,000	[units]	b_m	0.0012	[ton.year/unit^2]
γ	16,000	[units/year]	b_r	0.002	[ton.year/unit^2]
ν	16,000	[units/year]	c_m	1.4	[ton/unit]
S_m	1,100	[$/setup]	c_r	1.4	[ton/unit]
S_r	400	[$/setup]	c_{ec}	18	[$/ton]

Input Parameter	Value	Units	Input Parameter	Value	Units
h_p	300	[$/unit/year]	C_0'	57.96	[KWh/unit]
h_r	100	[$/unit/year]	C_1'	1,855,744	[KWh/year]
h_u	100	[$/unit/year]	C_0''	18.9	[KWh/unit]
c_{mr}	60,000	[$/unit]	C_1''	605,110	[KWh/year]
c_{re}	40,000	[$/unit]	c_{en}	0.0928	[$/KWh]
c_w	600	[$/unit]	g_t	375	[gallons/truck]
c_{inv}	18,000,000	[$/year]	e_t	0.01008414	[ton/gallon]
θ	0.2	[-]	t_c	2	[units/trucks]
a_m	0.0000003	[ton.year^2/unit^3]	F_t	10,000	[$/truck]

***Table 5.2** GHG emissions penalty scheme as given in Jaber et al. (2013)*

i	*Emission limit, i*	*Penalty charged, $C_{ep,i}$*
1	$Ed \leq L_1$	$C_{ep,1} = 0$
2	$L_1 \leq Ed < L_2$	$C_{ep,2}$
3	$L_2 \leq Ed < L_3$	$C_{ep,3}$
4	$L_3 \leq Ed < L_4$	$C_{ep,4}$
5	$L_4 \leq Ed < L_5$	$C_{ep,5}$
6	$Ed \geq L_5$	$C_{ep,6}$
	Where, $C_{ep,6} > C_{ep,5} > C_{ep,4} > C_{ep,3} > C_{ep,2} > C_{ep,1} = 0$	

Table 5.2 presents a general emissions penalty scheme similar to that presented in Jaber et al. (2013), who arbitrarily set the numbers in line with the European Union Emissions Trading System. The values suggested for the emissions limit and the associated penalty costs in Jaber et al. (2013) are suggested for a manufacturing process that operates between 1100 and 3000 production units per year with an optimal production rate computed at γ = 2000 units per year, where $\gamma = b_p/2a_p$. The numerical example provided in this study is a specific case that this model best resembles; that is, the tire remanufacturing industry, and most of the input parameters are

actual figures from the tire retread industry in Canada and its Oil Sands customers in Northern Alberta. However, to the authors' knowledge, no such values for the GHG emissions of this specific example are available, and considering the very high production rates considered in the numerical example, γ = 16000 units per year, GHG emissions generated will be of astronomical values in comparison to those suggested in Jaber et al. (2013). For that reason, a maximum emissions penalty is always considered in this numerical example where it is of value $15000 as per Jaber et al. (2013). This value is minute in comparison to the total costs of the system as presented below, however, if given a larger (smaller) value this will only shift the total cost curve up (down). To understand the step-wise shift of the total cost of the system, the GHG emissions and its effect on the GHG penalty based on the behavior of the production rate, the readers are referred to Bazan et al. (2015a).

For the literature review provided, firms have solely focused on optimizing the supply chain and reverse logistics cost, but ignored environmental costs such as GHG emissions released from production and transportation activities and the total energy used for production. This has been the traditional focus of reverse logistics models so far. Optimizing the system, i.e. Eqs. (5.1)-(5.7), while ignoring GHG emissions and energy usage costs yields the following total annual cost of $243,776,308 with a manufacturing batch size of $Q = 123.93$ units and remanufacturing batch size of $R = 200.91$ at the optimal policy of $n = 1$ manufacturing batches, $m = 1$ remanufacturing batches and a tire is remanufactured $\zeta = 4$ times before it has to be disposed of through a cycle time of $T = 0.081$ years. The annual supply chain cost for this policy is $233,749,101 and $10,027,207 is the sum of GHG emissions and energy usage costs.

Applying the appropriate formula presented in Section 5.3, Eq. (5.13), and optimizing for the total costs (including the environmental GHG emissions and energy usage costs) yields a minimum annual total cost of $243,682,202 with a manufacturing batch size of $Q = 133.90$ units and a remanufacturing batch size of $R = 190.10$ at the optimal policy of $n = 1$ manufacturing batches, $m = 1$ remanufacturing batches and $\zeta = 3$ where $T = 0.081$ years. For this policy, the annual supply chain cost is $233,940,795 and $9,741,407 is the sum of GHG emissions and energy usage costs. It is clear from the results that the annual supply chain cost has slightly increased, but as a result of the more significant decrease in the GHG emissions and the energy usage costs the overall system costs are less ($94,106 per year).

Two main results should be noted: first, there is a reduction of $285,800 in the GHG emissions and energy usage costs, which reflects a significant improvement in the environmental conditions as there are less GHG emissions released and less energy used, and secondly is that the optimal number of times to remanufacture a product has decreased indicating increasing the number of times a tire may be remanufactured may not necessarily be saving the environment. This is contrary to studies that ignored these costs as the only benefit they see is from reducing solid waste disposal through remanufacturing.

For the same input parameters, the model has been solved for $0 \leq \zeta \leq 10$ while optimizing for n and m (see Figure 5.3). The results show that the highest total cost is when there is no remanufacturing considered ($\zeta = 0, m = 0, n = 1$). For this scenario the results show that the total GHG emissions for this scenario is the lowest: GHG from manufacturing is highest, but no emissions from remanufacturing as there is none, and low emissions from transportation as there are no trucks returning from the market contributed to this (see Figure 5.4). Energy usage gradually decreases as ζ is increased with the minimum amount of energy used occurring when ζ =10. In spite of an increase in the energy used to remanufacture, the reduction in energy used for manufacturing is significantly reduced resulting in the overall decrease (see Figure 5.5). Clearly, as the number of times to remanufacture increases, the cost of solid waste disposal and the number of items scrapped decrease (see Figure 5.6). Ultimately, if the focus is on reducing GHG emissions, the decision would be to not remanufacture, but this will be detrimental to other environmental concerns as discussed.

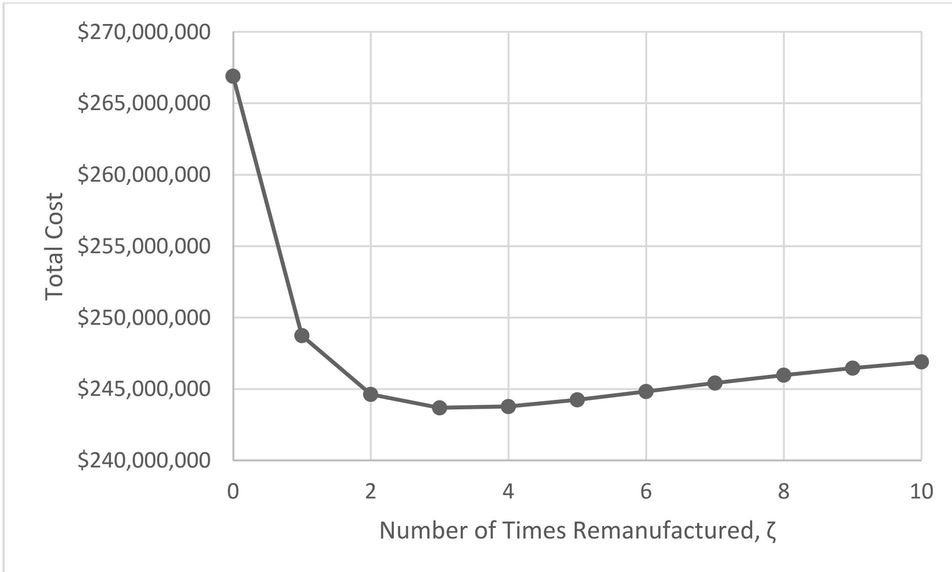

Fig. 5.3 *Optimal (minimum) cost for different values of ζ*

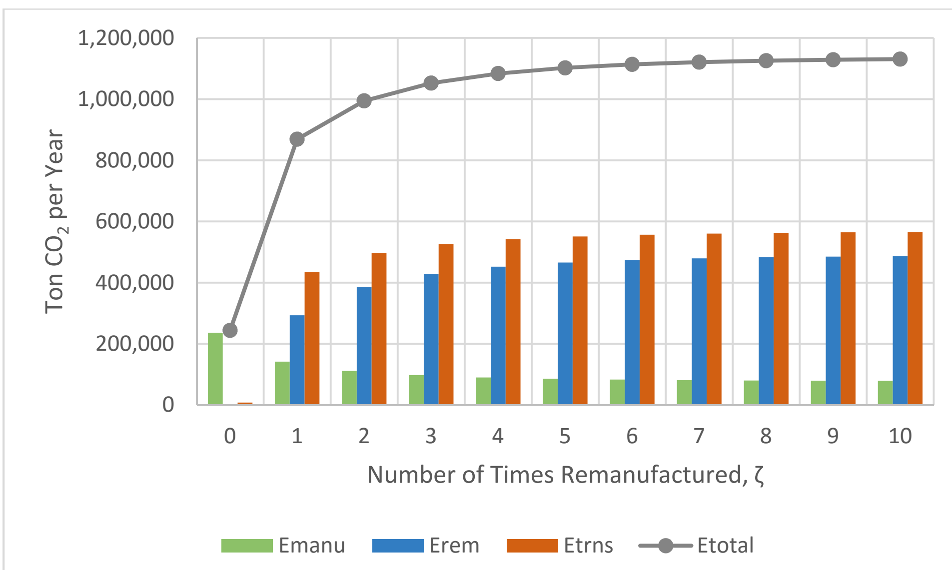

Fig. 5.4 *Amount of GHG emissions for optimal scenarios at different values of ζ*

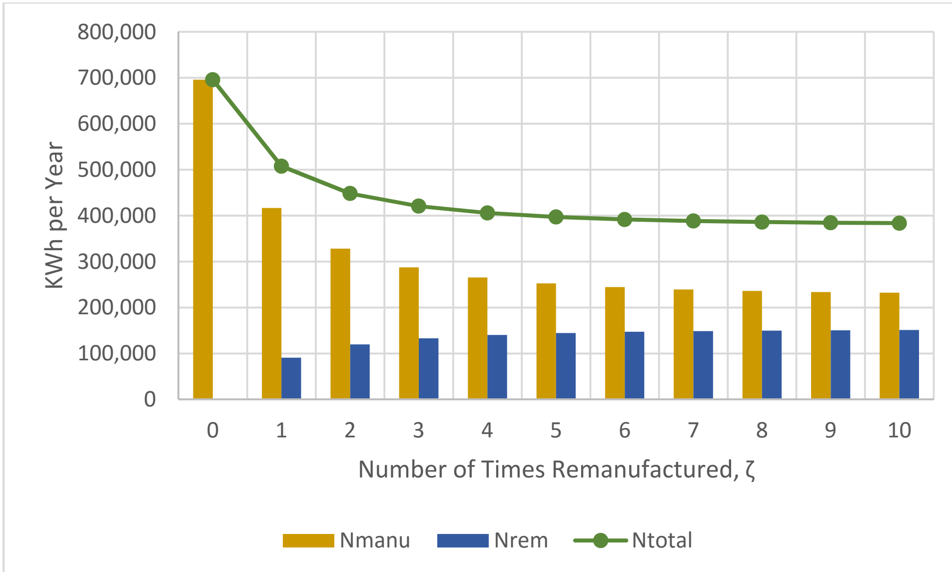

Fig. 5.5 *Amount of energy used per year for optimal scenario at different values of* ζ

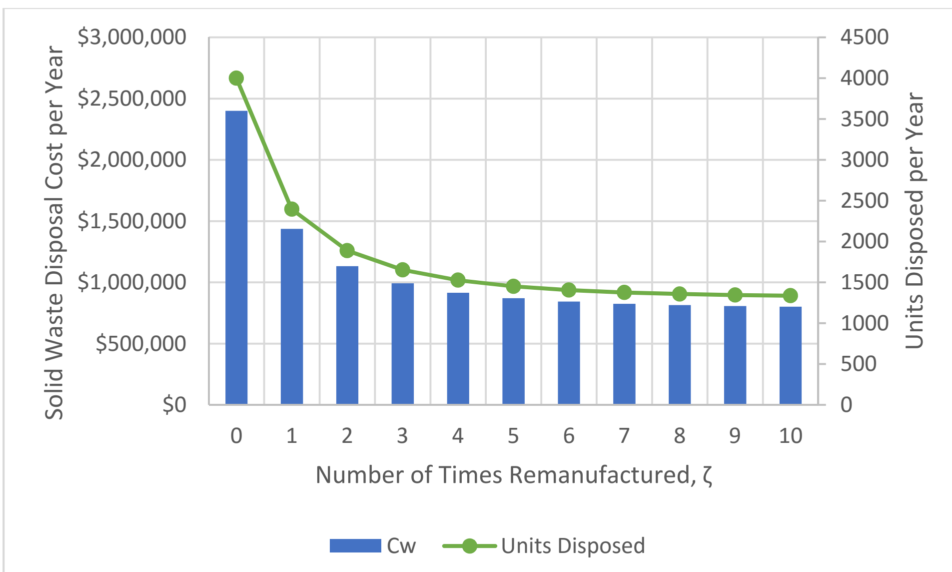

Fig. 5.6 *Number of units wasted and their associated disposal cost for optimal scenarios at different values of* ζ

An important component of a reverse logistics system, and especially the tire remanufacturing industry, is recollecting the sold items, i.e. the availability of "cores" (United States International Trade Commission, 2012). To study this effect, the model has been optimized for $0 \leq \beta \leq 0.9$ (increments of 0.05). The results show that as more tires are collected from the market the more the optimal solution pushes to remanufacture. Moreover, this coincides with a general reduction in the overall costs highlighting the importance of increasing the number of cores available for remanufacturing. Shifting the focus to GHG emissions, increasing the core availability yields more emissions since the number of times to remanufacture is increased with more core. This is a result of reduced emissions from manufacturing, but large increases in the amount of emissions from remanufacturing and transportation (see Figure 5.7). Regarding energy, the energy usage will constantly decrease for the same values of n and m, but an increase in m (increasing remanufacturing batch size) will cause a more significant reduction as can be noted in the results for the ranges $0.05 \leq \beta \leq 0.15$ (see Figure 5.8). Excluding the case of no remanufacturing, it can also be shown that for cases where there are more manufacturing batches than remanufacturing batches, and there is a considerable amount of energy used that exceeds any of the other cases highlighting the fact that energy usage for manufacturing is excessive compared to energy usage for remanufacturing (see Figure 5.9). Clearly, the availability of cores is not only important to the economics of a reverse logistics model, but also very critical to the environmental issue of energy consumption where more available cores is beneficiary, but this does conflict with the environmental issue of GHG emissions released where significant harm is a result due to the increasing amount of total GHG emissions released into the air.

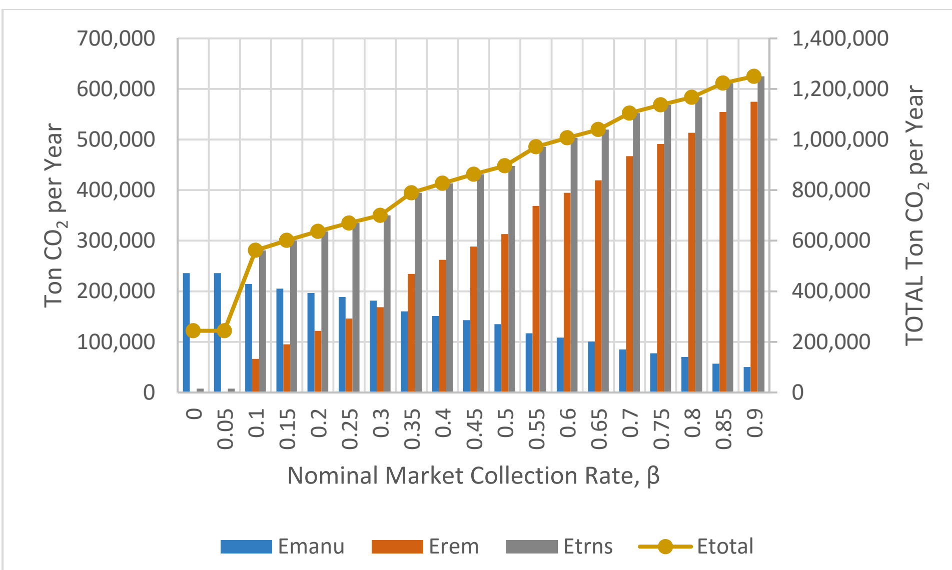

Fig. 5.7 *Amount of GHG emissions released for optimal scenarios for different values of* β

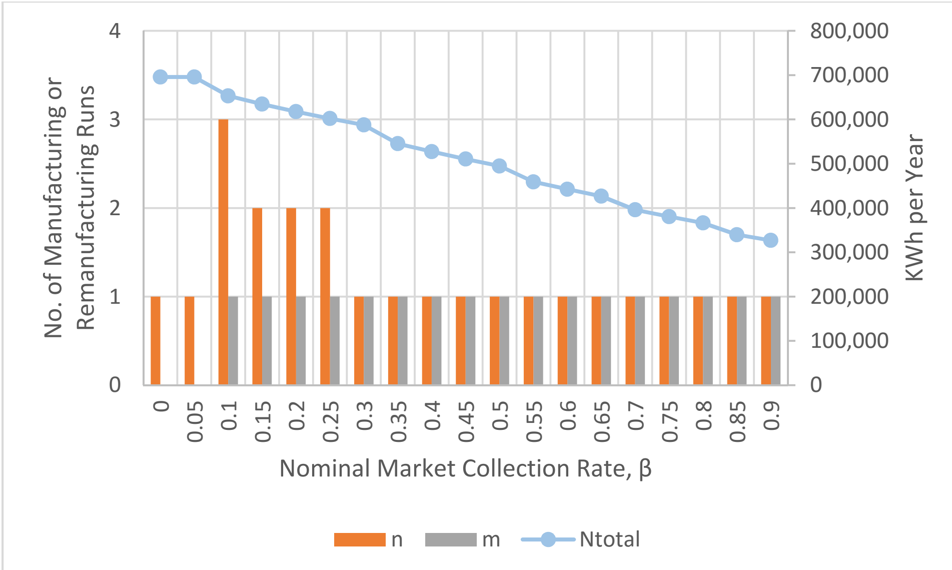

Fig. 5.8 *Optimal* $\{n, m\}$ *decision variable values and associated total energy usage cost for different values of* β

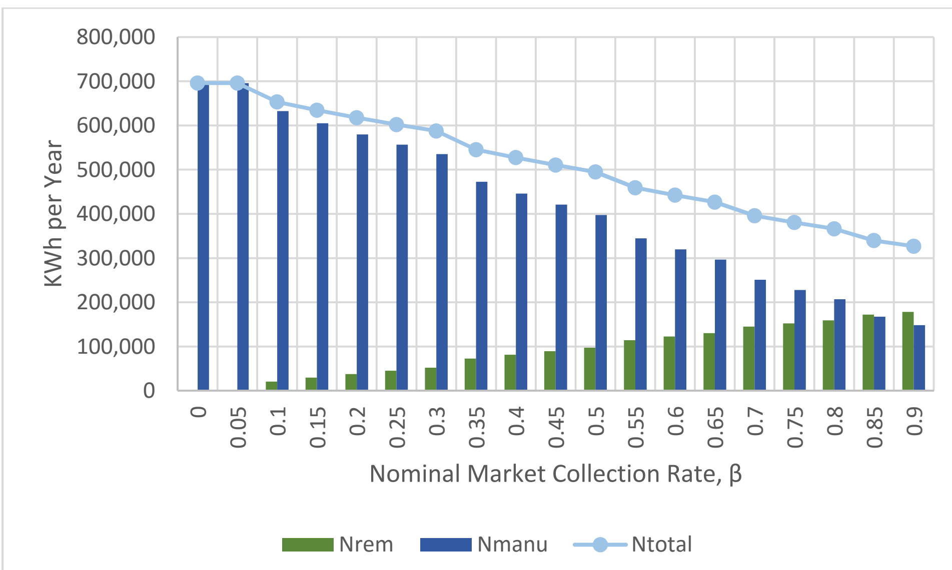

Fig. 5.9 *Manufacturing and remanufacturing energy usage for optimal scenarios at different values of* β

In general, optimizing for all environmental costs, as opposed to the 'traditional' method of optimizing reverse logistics system costs, ignoring GHG emissions and energy usage, was more beneficiary financially and less harmful to the environment when considering all environmental concerns: solid waste disposal, GHG emissions released and energy used. The different scenario presented show that optimality for one environmental factor alone is not a judicious choice since the different environmental factors have conflicting objectives.

5.5. Discussion

The following section presents discussion points that lead to insights beyond the results of this chapter. The section focuses on two main aspects: managerial insights that can assist decision makers in the industry, and discussions pertaining to the limitations of the current work.

From the results presented in Section 5.4 it is evident that there are economic and environmental benefits to a production inventory system in which remanufacturing is present. The true system costs can only be presented when considering environmental costs other than just solid waste disposal, namely: GHG emissions and energy usage. When one considers the impact of all three environmental issues the results show that there is a need to promote less remanufacturing to protect the environment. Furthermore, the results show that including GHG emissions and energy usage in the objective function help reduce the overall system costs, adding an economic benefit to the environmental savings. Certainly, management and concerned stakeholders must take into account what are the main environmental objectives to be realized: a collective improvement in the environmental conditions of the system as presented by the optimization of the proposed model, or are there individual targets to be met? As the results show, focusing on a specific environmental aspect may harm the other aspects. Is there a push from government to reduce GHG emissions: is this actually of benefit to the overall environmental conditions or do the objectives need to be revised? One must not oversee the improvement of a specific environmental factor to the detriment of others: a balance is to be achieved.

Generally, the best results of the simulation runs were achieved when the availability of the ‘cores’ (used products collected for remanufacturing) was increased. This suggests management is needed to achieve this. Certain products have established leasing options such as those for vehicles and/or general office equipment like photocopy machines that facilitate products to be returned with ease by the customer. However, buyback promotions and other incentives may also be proposed. While all these options seem promising, they all focus on collecting used products produced by a manufacturer and do not tap into competitive markets. Competitor products may be similar, but in order for them to be remanufactured, they may require additional steps to prepare the product as a result of different designs and materials used. These may make the remanufacturing process a bit more costly in addition to the cost of acquisition from the respective markets. Nonetheless, their availability increases the economic and environmental benefits from remanufacturing given their feasibility.

Given challenges to retrieve products from competitors' markets, decision makers could look into remanufacturing components or sub-assemblies of a product. Clearly, such an option may be more feasible and more cost efficient. Investigation regarding reverse logistics inventory models and remanufacturing sub-assemblies has been explored in El Saadany and Jaber (2011), however, they have yet to be explored from an environmental perspective as has been suggested in this paper. Similar to remanufacturing the product as a whole, but to a larger extent, the prerequisite for an efficient remanufacturing model for components and sub-assemblies is in the design of the product. Consideration of different Design for X categories (Bishop, 2000) such as Design for Manufacturability (DfM), Design for Disassembly (DfD), Design for Environment (DfE) become of significant importance. Not only must a product be designed for ease in manufacturing, but also for disassembly to facilitate remanufacturing, and for environment to find alternative environmentally friendly materials – i.e., those that are more biodegradable upon disposal, those that require less energy for extraction and production, and/or those that emit less GHG emissions throughout the production process.

Another important aspect to consider is technological advancements in a product that may lead to new market demands and possible obsolescence. For example, recent testing is being implemented to military vehicles as well as other light weight vehicles where the tires are airless. Such advancement may lead to the obsolescence of current tires and their manufacturing process which in turn will have a negative impact on the economics of a manufacturing/remanufacturing reverse logistics system. Even though such a technology may be in its infancy stage of development, other products like the cathode-ray computer monitor have been replaced by thin, light weight, energy efficient LCD and LED monitors in a short amount of time. Needless to say other computer accessories, like the floppy disc, the dot-matrix printer are no longer in use; further, compact discs (CDs) and CD players are soon to be obsolete products. The discussion quickly becomes one regarding the nature of the product and its expected lifetime before it is no longer in demand. Once a product is no longer required, remanufacturing as a whole is not an option, but the possibility of remanufacturing certain components can be, say the remanufacturing of specific components or sub-assembly of a fridge or home appliance. However, again, certain technological advancements may be present where a new fridge is more energy efficient and hence the remanufacturing of a used one is of a lesser standard and if not met with a reduction in price, is not sold. That is to say, the argument is now two-fold; we not only must be aware of possible obsolescence, but also look at the assumption that a remanufactured product be considered 'as-good-as-new'.

Recycling is an option that has not been presented in the proposed model, yet its inclusion may be necessary when considering the examples presented regarding the technological advancements of products. In comparison to remanufacturing, recycling is a very energy intensive operation. Furthermore, recycling reduces the value of a product whereas remanufacturing increases the value of a used product (or recovers the value) (Sundin and Lee, 2012). As a result, in the hierarchy of product recovery, remanufacturing is more preferred to recycling. However, if a product has a high obsolescence rate, then remanufacturing may not be preferred, possibly remanufacturing of certain components, but what becomes a means to salvage material instead of a total loss is recycling. On the other hand, if a product is relatively steady, then recycling, which is an energy intensive process, will reduce the product value and what should be promoted is remanufacturing or partial remanufacturing at least.

The current model is not without limitations. Undoubtedly, the consideration of acquiring more used products from the market, Design for X costs and their effect on the product, product obsolescence, remanufacturing of individual components and assemblies, and recycling will all add to the development of reverse logistics models. Beyond these extensions other environmental issues such as chemical and toxic wastes, other air emissions, water contamination, biodegradability of products in landfill sites, thermal pollution, and noise should be considered as well. The true accounting for all environmental issues will help promote a holistic approach to optimal policy decision making that will promote environmental sustainability. Other limitations of this work include the assumed mode of transport to be that of diesel trucks. Moreover, the assumption of a single-level system where there is no retailer between the production facility (manufacturer/remanufacturer) and the end customer in the market. The proposed model is by no means an end result, but rather opens the door to develop reverse logistic inventory models that are environmentally responsible.

5.6 Summary and Conclusions

This chapter presented a model that captures the traditional costs of a manufacturing-remanufacturing reverse logistics inventory system along with costs for GHG emissions from manufacturing, remanufacturing and transportation, as well as costs for energy usage required for manufacturing and remanufacturing. The proposed model is seen as a preliminary step into developing an environmentally responsible reverse logistics inventory model.

The results showed that optimizing for financial costs and all environmental costs will promote less remanufacturing to protect the environment as opposed to just focusing on solid waste disposal which has been the focus of previous 'traditional' reverse logistic models that consider remanufacturing. In addition, results show the need to increase the recollection of available used products that can be remanufactured.

Future work include relaxing modeling assumptions that limit the work to land transportation, consideration of various retailers, the assumption remanufactured items are 'as good as new' and that items can be partially remanufactured as components or sub-assemblies. Other research extensions include recycling options for material recovery and to study the effect of implementing Design for X categories.

Chapter 6

CARBON EMISSIONS AND ENERGY EFFECTS ON A TWO-LEVEL MANUFACTURER-RETAILER CLOSED-LOOP SUPPLY CHAIN MODEL WITH REMANUFACTURING SUBJECT TO DIFFERENT COORDINATION

This chapter combines the models discussed in Chapters 4 and 5 and presents a closed-loop supply chain model with a manufacturer and a retailer for a single product case. Elements of this chapter are taken from the paper Bazan et al. (in preparation) to be submitted for review in the International Journal of Production Economics - Special Issue).

6.1 Introduction

A closed-loop supply chain (CLSC), which is encompassed by a green supply chain, considers forward and reverse flows of a product to and from the market either as new or as recovered (e.g., remanufacture, refurbished). The model of this chapter also accounts for environmental costs, namely those from carbon emissions and energy usage, in an attempt of factoring "the green concept' into a firm's decisions.

6.2 Model Concept, Main Assumptions and Nomenclature

The model developed in this chapter integrates the models presented in chapter 4, two-level forward supply chain model (Bazan et al. 2015a), and chapter 5, a single-level reverse logistics model, (Bazan et al. 2015b). The model studies the effects of carbon emissions and energy usage on production, remanufacturing, waste disposal, and lot sizing and shipment decisions in a CLSC operating under different coordination mechanisms. Several managerial insights and suggestions are presented that argues towards the need to design environmentally responsible and economically viable inventory and logistics systems.

The model considered in this chapter is a manufacturer that produces and ships items (of a product) to a retailer in batches following one if two coordination mechanisms: (1) classical, or a (2) Vendor Managed Inventory with Consignment Stock (VMI-CS). The model also considers the collection of used items from the market by the retailer, who sends them back to the manufacturer for recovery. The quality of remanufactured items is considered to be as-good-as-new. The production and remanufacturing process are always in control suggesting that there are no defective items to be reworked or scrapped. Used items are recovered as whole units suggesting that no sub-assemblies or components are considered. The description of the CLSC model and the flow of items is depicted in Figure 6.1.

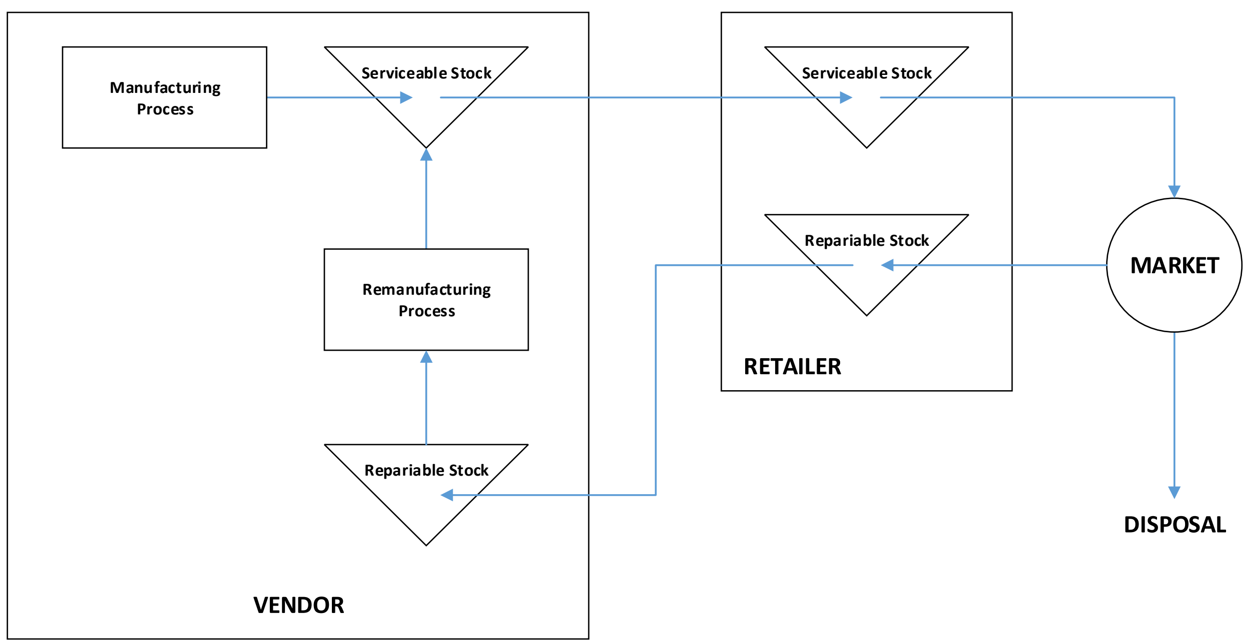

Figure 6.1 *Forward and reverse material flow throughout the inventory system*

Similar to models in Chapters 4 and 5, the manufacturing and remanufacturing facilities are considered predominantly machine tools. Energy usage by the system main processes and transportation of goods between the vendor (manufacturer) and buyer (retailer) are considered. It is assumed here that trucks represent the mode of Carbon emissions (GHG emissions) released from manufacturing and remanufacturing processes and from transportation activities are also considered. The European Union Emissions Trading System suggests a penalty tax (Jaber et al., 2013) that is applied to the collective GHG emissions emitted by the system from all sources. The total annual cost for the system described in Fig. 6.1 includes:

1. Holding cost for serviceable stock (manufactured and remanufactured items) at the vendor's side
2. Holding cost for repairable stock (used items collected to be remanufactured) at the vendor's side
3. Holding cost for serviceable stock (manufactured and remanufactured items) at the buyer's side
4. Holding cost for repairable stock (used items collected to be remanufactured) at the buyer's side
5. Production (manufacturing and remanufacturing) setup cost at the vendor's side
6. Batch ordering cost at the buyer's side
7. Unit production (manufacturing and remanufacturing) cost at the vendor's side
8. Cost of investment in the design process. A function of the number of items an item can be remanufactured
9. Cost of waste disposal (products that can no longer be remanufactured)
10. Transportation cost
11. Cost of GHG emissions from production (manufacturing and remanufacturing)
12. Cost of GHG emissions from transportation
13. GHG emissions penalty cost for exceeding the emission cap.
14. Cost of energy used for production (manufacturing and remanufacturing)

The total cost function, which is the sum of the 14 cost components listed above, is minimized. For classical coordination, the buyer (retailer) and the manufacturer agree to the number and size of shipments that minimises the total system cost. We assume that the savings from coordination shared by both parties according to some contract; profit (savings) sharing scenarios is no considered here. The batches shipped to the buyer could comprise of pure remanufactured or manufactured items, or mixed. For VMI-CS coordination the vendor (manufacturer) stores its inventory at the buyer's side and manages it. This gives the manufacturer the flexibility to ship batches of different sizes at different times, where the manufacturer can avoid a mixed production batch. The decision variables that optimize the total cost function for the classical coordination are: the batch (shipment) size, the number of shipments per vendor's cycle, and the number of times an item can be remanufactured. The decision variables for the VMI-CS coordination model are: the size of a manufacturing batch, the number of shipments of remanufactured batches, the number of shipments of manufactured batch size, and the number of times an item can be remanufactured. Figures 6.2, 6.2a, 6.2b, and 6.2c illustrate the inventory behaviour for the supply chain with classical coordination. Figure 6.3 illustrate the inventory behaviour for the supply chain with VMI-CS. Decision variables, input parameters and other parameters for the both models are defined below.

Decision Variables for the Classical Coordination model

- Q The production batch size per cycle [units]
- k The number of shipments of batch size Q, where $k \geq 1$ and integer
- ζ The number of times an item is remanufactured, where $\zeta \geq 0$ and integer

Decision Variables for the VMI-CS Coordination model

- Q The manufacturing batch size per cycle [units]
- ζ The number of times an item is remanufactured, where $\zeta \geq 0$ and integer
- m The number of pure remanufacturing production batches, where $m \geq 1$ and integer
- n The number of pure manufacturing production batches, where $n \geq 1$ and integer

It should be noted that Q is defined as the production batch in the classical coordination model as it may include a mixed batch. It is defined as the manufacturing batch size in the VMI-CS model.

Input and Other Parameters

- d The demand rate (deterministic and constant), [units/year]
- γ The manufacturing rate, where $\gamma > d$, [units/year]
- ν The remanufacturing rate, where $\nu > d$, [units/year]
- β The nominal proportion of items returned for remanufacturing when an item is remanufactured for an unlimited number of times, where $0 \leq \beta \leq 1$

β_ζ	The actual proportion of items returned for recovery. An item is recovered for a limited ζ number of times, where $\beta_\zeta = 1 - \left[\frac{(1-\beta)}{(1-\beta^{\zeta+1})}\right]$
R	The remanufacturing batch size per cycle [units], where $R = \frac{\beta_\zeta nQ}{(1-\beta_\zeta)m}$, [units] and is only applicable for the VMI-CS coordination model
T	Vendor's cycle time, where $T = \frac{kQ}{d}$ for classical coordination and $T = \frac{nQ+mR}{d}$ for VMI-CS coordination [year]
λ	The number of batch shipments from the vendor to the buyer during the production (manufacturing or remanufacturing) segment of T
h_{p_v}	The holding cost for a manufactured unit of serviceable stock at the vendor's side, [$/unit/year]
h_{r_v}	The holding cost for a remanufactured unit of serviceable stock at the vendor's side, where $h_{p_v} \neq h_{r_v}$, [$/unit/year]
h_{u_v}	The holding cost for a returned unit of the repairable stock at the vendor's side, where $h_{p_v} > h_{r_v} > h_{u_v}$, [$/unit/year]
h_{p_b}	The holding cost for a manufactured unit of serviceable stock at the buyer's side, [$/unit/year]
h_{r_b}	The holding cost for a remanufactured unit of serviceable stock at the buyer's side, where $h_{p_b} \neq h_{r_b}$, [$/unit/year]
h_{u_b}	The holding cost for a returned unit of repairable stock at the buyer's side, where $h_{p_b} > h_{r_b} > h_{u_b}$, [$/unit/year]
h'_v	The adjusted unit holding cost for serviceable stock at the vendor's side, where $h'_v = (1-\beta_\zeta)h_{p_v} + (\beta_\zeta)h_{r_v}$, [$/unit/year]
h'_b	The adjusted unit holding cost for serviceable stock at the buyer's side, where $h'_b = (1-\beta_\zeta)h_{p_b} + (\beta_\zeta)h_{r_b}$, [$/unit/year]
S_m	The manufacturing setup cost, [$]
S_r	The remanufacturing setup cost, [$]
O_b	The remanufacturing order cost, [$]
c_{m_r}	The unit manufacturing cost, [$/unit]

c_{r_e}	The unit remanufacturing cost, [$/unit]
c_{inv}	The annual investment in the design process, theoretically, to be able to remanufacture an item for an indefinite number of times, [$/year]
θ	Governing parameter representing the ratio of investment for each remanufactured generation, where $0 \leq \theta < 1$
c_w	The unit disposal cost, [$/unit]
F_t	The fixed cost per truck per trip, [$/truck]
t_c	The truck capacity, [units/truck]
c_{ec}	The tax per ton of GHG emissions, [$/ton]
a_p	An emissions function parameter for manufacturing, [ton.year^2/unit^3]
b_p	An emissions function parameter for manufacturing, [ton.year/unit^2]
c_p	An emissions function parameter for manufacturing, [ton/unit]
a_r	An emissions function parameter for remanufacturing, [ton.year^2/unit^3]
b_r	An emissions function parameter for remanufacturing, [ton.year/unit^2]
c_r	An emissions function parameter for remanufacturing, [ton/unit]
g_t	The number of gallons per truck per distance travelled, [gallons/truck]
e_t	The amount of GHG emissions from one gallon of diesel-truck fuel, [ton/gallon]
E	Total annual greenhouse gas (mainly CO_2) emissions from all sources (ton/year)
L_i	Emissions limit i (ton/year);
x	Number of emissions limits;
C_0'	A coefficient (inverse) of the manufacturing energy usage function, [kWh/unit]
C_1'	A coefficient (predictor) of the manufacturing energy usage function, [KWh/year]
C_0''	A coefficient (inverse) of the remanufacturing energy usage function, [kWh/unit]
C_1''	A coefficient (predictor) of the (remanufacturing energy usage function), [KWh/year]
c_{en}	Cost of energy [$/KWh]

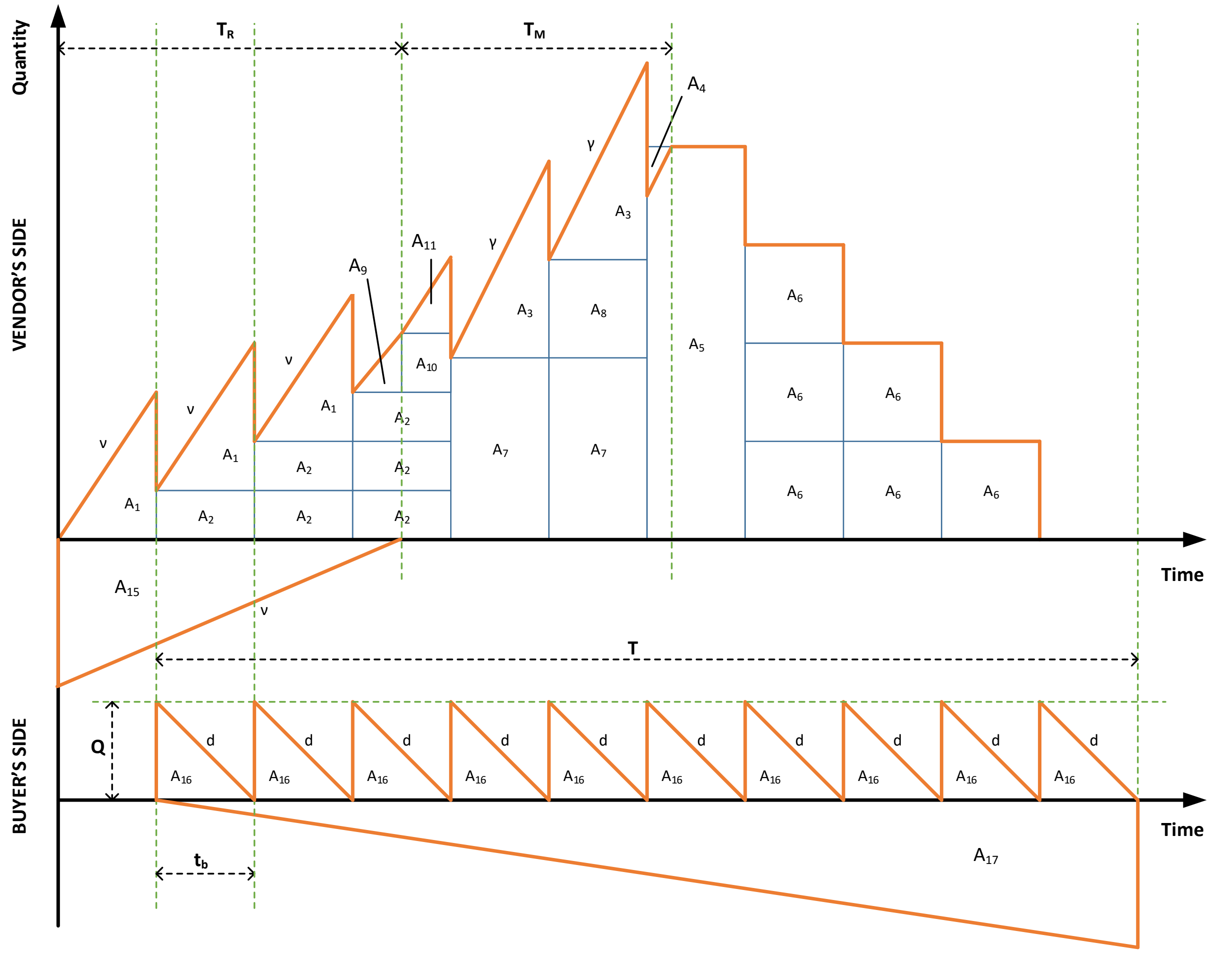

Figure 6.2 *Inventory behavior at the vendor and buyer's side for a two-level manufacturer-retailer supply chain with classical coordination (*$k = 10$*,* $\lambda = 6$*,* $m = 3$*,* $n = 3$*,* $\vartheta = 1$*,* $\varphi = 1$*,* $\omega = 0$*)*

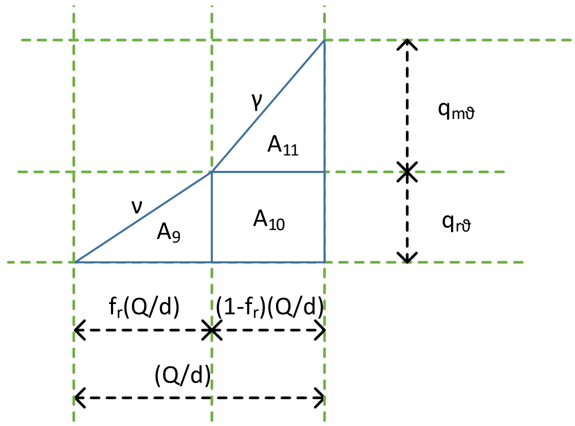

Figure 6.2a *Inventory behaviour of the mixed production batch at the vendor's side when* $T_M \geq (1 - f_r)\frac{Q}{d}$ *(i.e., when* $\omega = 0$*)*

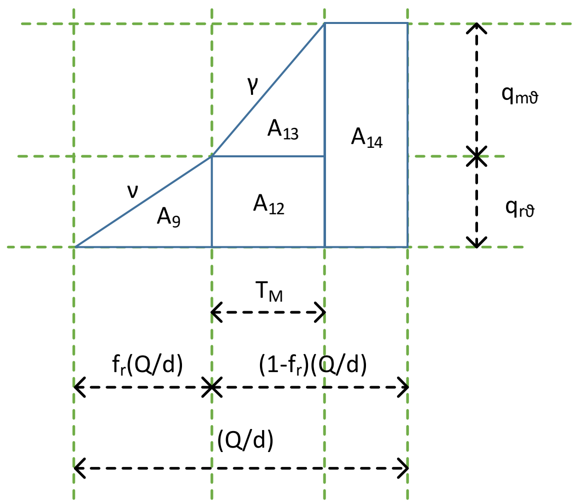

Figure 6.2b *Inventory behaviour of the mixed production batch at the vendor's side when* $T_M < (1 - f_r)\frac{Q}{d}$ *(i.e., when* $\omega = 1$*)*

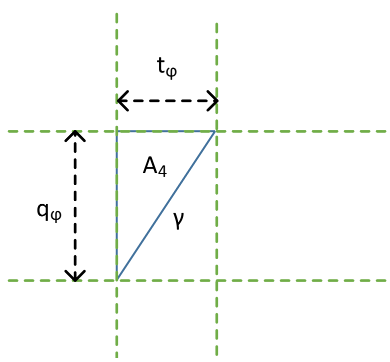

Figure 6.2c *Area* A_4 *that is subtracted from area* A_5 *to calculate the inventory holding cost when* $\varphi = 1$

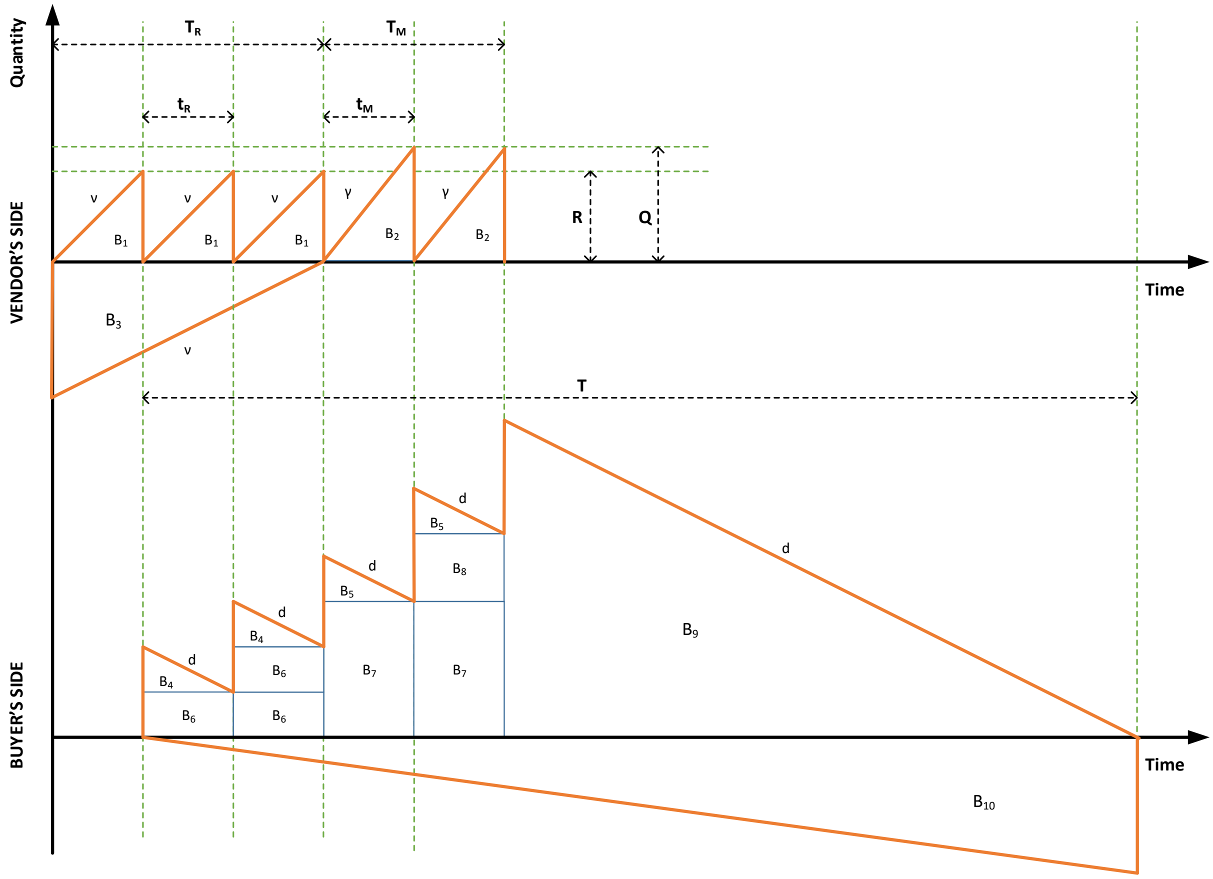

Figure 6.3 *Inventory behaviour at the vendor and buyer's side for a two-level manufacturer-retailer supply chain with VMI-CS coordination* ($m = 3$, $n = 2$, $k = 5$, $\lambda = 5$)

6.3 Cost Functions

The cost functions for the classical and VMI-CS coordination models are developed in this section.

Referring to Figure 6.2, the time to remanufacture the collected repairable stock (in years) is written as:

$$T_R = \frac{\beta_\zeta d T}{\nu} \tag{6.1}$$

From Figure 6.2, the time of one interval (in years) is written as:

$$t_b = \frac{Q}{d} \tag{6.2}$$

The number of pure remanufacturing batches per cycle is given as the lower integer dividing Eqs. (6.1) and (6.2):

$$m = \left\lfloor \frac{(\beta_\zeta dT)/_v}{Q/_d} \right\rfloor = \lfloor \beta_\zeta dk/v \rfloor \tag{6.3}$$

The fraction of t_b to remanufacture items when the batch is mixed:

$$f_r = (\beta_\zeta dk/v) - \lfloor \beta_\zeta dk/v \rfloor \tag{6.4}$$

Where $(1 - f_r)$is the fraction of t_b to manufacture items when the batch is mixed (for the case presented in Figure 6.2a). The time to manufacture (in years) is given as:

$$T_M = \frac{kQ - \beta_\zeta dT}{\gamma} \tag{6.5}$$

Where $T_M \geq (1 - f_r)\frac{Q}{d}$, otherwise the time is defined by T_M and the remaining time of the mixed batch has no production (see Figures 6.2a and 6.2b).

If the total amount to manufacture is less than t_b then:

$$\omega = \begin{Bmatrix} 1, \left(\frac{dk}{\gamma}(1 - \beta_\zeta)\right) - (1 - f_r) < 0 \\ 0, \quad otherwise \end{Bmatrix} \tag{6.6}$$

Similarly to Eq. (6.3), the number of pure manufacturing batches per cycle can be calculated as:

$$n = \left\{ \begin{array}{ll} \left\lceil \dfrac{\left(\frac{kQ-\beta_\zeta dT}{\gamma}\right)-\left((1-f_r)\frac{Q}{d}\right)}{Q/d} \right\rceil = \left\lceil \left(\frac{dk}{\gamma}\left(1-\beta_\zeta\right)\right)-(1-f_r) \right\rceil & ,\omega = 0 \\ 0 & ,\omega = 1 \end{array} \right\} \tag{6.7}$$

Also, the fraction of t_b that is required for a smaller addition of a manufacturing batch is:

$$f_m = \left\lceil \left(\frac{dk}{\gamma}\left(1-\beta_\zeta\right)\right)-(1-f_r) \right\rceil - \left(\left(\frac{dk}{\gamma}\left(1-\beta_\zeta\right)\right)-(1-f_r)\right) \tag{6.8}$$

Define:

$$\vartheta = \begin{Bmatrix} 1 & ,f_r > 0 \\ 0, & \text{otherwise} \end{Bmatrix} \tag{6.9}$$

$$\varphi = \begin{Bmatrix} 1 & ,f_m > 0 \\ 0, & \text{otherwise} \end{Bmatrix} \tag{6.10}$$

That is, $\vartheta = 1$ a mixed batch occurs, and $\varphi = 1$ means there is a smaller/additional to the manufacturing batch is required and the number of shipments during production is:

$$\lambda = (m + \vartheta) + (n - \varphi) \tag{6.11}$$

The fundamental assumption of the model is that there is remanufacturing (else, it reduces to the classical coordination model of Bazan et al., 2015a) previously discussed in Chapter 4. This implies that $m + \vartheta \geq 1$ and $n + \vartheta \geq 1$ should be satisfied such that at least one manufacturing and remanufacturing batch are present, or at least a mixed production batch is present.

The annual holding costs is the average inventory level (by calculating A_i for $i = 1$ to 17 as per Figures 6.2, 6.2a, 6.2b and 6.2c) and multiplying it by the respective unit holding cost and then dividing it by the cycle time. Then, the annual holding cost of the serviceable stock at the vendor's side is written as:

$$H_{ser_v} = \frac{\left(\sum A_1 + \sum A_2 + \sum A_3 + \varphi(A_5 - A_4) + \sum A_6 + \sum A_7 + \sum A_8 + \vartheta A_9 + \vartheta(1-\omega)(A_{10} + A_{11}) + \vartheta\omega(A_{12} + A_{13} + A_{14})\right) h'_v}{T} \quad (6.12)$$

Where:

$$\sum A_1 = mA_1 = \frac{mv}{2}\left(\frac{Q}{d}\right)^2 \quad (6.12a)$$

$$\sum A_2 = \frac{(m+\vartheta)(m+\vartheta-1)}{2} A_2 = \frac{(m+\vartheta)(m+\vartheta-1)}{2}\left(\frac{Q^2}{d}\left(\frac{v}{d} - 1\right)\right) \quad (6.12b)$$

$$\sum A_3 = (n - \varphi)A_3 = \frac{(n-\varphi)\gamma}{2}\left(\frac{Q}{d}\right)^2 \quad (6.12c)$$

$$A_4 = \frac{1}{2} t_\varphi q_\varphi = \frac{Q^2}{2}\left(\left(\frac{k}{\gamma}(1 - \beta_\zeta)\right) - \left(\frac{1}{d}(n - \varphi + 1 - f_r)\right)\right) \times$$
$$\left(\left(k(1 - \beta_\zeta)\right) - \left(\frac{\gamma}{d}(n - \varphi + 1 - f_r)\right)\right) \quad (6.12d)$$

$$\mathrm{A_5} = (\mathrm{k} - \lambda)\frac{\mathrm{Q^2}}{\mathrm{d}} \quad (6.12e)$$

$$\sum \mathrm{A_6} = \phi \frac{(\mathrm{k} - \lambda)(\mathrm{k} - \lambda - 1)}{2}\mathrm{A_6} + (1 - \phi)\frac{(\mathrm{k} - \lambda + 1)(\mathrm{k} - \lambda)}{2}\mathrm{A_6}$$
$$= \phi \frac{(\mathrm{k} - \lambda)(\mathrm{k} - \lambda - 1)}{2}\left(\frac{\mathrm{Q^2}}{\mathrm{d}}\right) + (1 - \phi)\frac{(\mathrm{k} - \lambda + 1)(\mathrm{k} - \lambda)}{2}\left(\frac{\mathrm{Q^2}}{\mathrm{d}}\right) \quad (6.12f)$$

$$\sum \mathrm{A_7} = (\mathrm{n} - \phi)\mathrm{A_7} = (\mathrm{n} - \phi)\left(\left(\mathrm{m}\left(\frac{\mathrm{Q}}{\mathrm{d}}\nu - \mathrm{Q}\right) + \vartheta(\mathrm{q_{r\vartheta}} + \mathrm{q_{m\vartheta}} - \mathrm{Q})\right)\frac{\mathrm{Q}}{\mathrm{d}}\right)$$
$$= \frac{\mathrm{Q^2}(\mathrm{n} - \phi)}{\mathrm{d}}\left(\mathrm{m}\left(\frac{\nu}{\mathrm{d}} - 1\right) + \vartheta\left(\mathrm{f_r}\frac{\nu}{\mathrm{d}} + (1 - \mathrm{f_r})\frac{\gamma}{\mathrm{d}} - 1\right)\right) \quad (6.12g)$$

$$\sum \mathrm{A_8} = \frac{(\mathrm{n} - \phi)(\mathrm{n} - \phi - 1)}{2}\mathrm{A_8} = \frac{(\mathrm{n} - \phi)(\mathrm{n} - \phi - 1)}{2}\left(\frac{\mathrm{Q^2}}{\mathrm{d}}\left(\frac{\gamma}{\mathrm{d}} - 1\right)\right) \quad (6.12h)$$

$$A_9 = \frac{1}{2} f_r \left(\frac{Q}{d}\right) q_{r\vartheta} = \frac{\nu}{2} f_r^2 \left(\frac{Q}{d}\right)^2 \quad (6.12i)$$

$$A_{10} = (1 - f_r) \frac{Q}{d} q_{r\vartheta} = f_r(1 - f_r)\, \nu \left(\frac{Q}{d}\right)^2 \quad (6.12j)$$

$$A_{11} = \frac{1}{2} (1 - f_r) \frac{Q}{d} q_{m\vartheta} = \frac{\gamma}{2} (1 - f_r)^2 \left(\frac{Q}{d}\right)^2 \quad (6.12k)$$

$$A_{12} = q_{r\vartheta} T_M = \left(\frac{Q^2}{d}\right) f_r \left(\frac{k\,\nu}{\gamma}\right) \left(1 - \beta_{\zeta}\right) \quad (6.12l)$$

$$A_{13} = \frac{1}{2} q_{m\vartheta} T_M = \frac{kQ^2}{2d} \left(1 - \beta_{\zeta}\right)(1 - f_r) \quad (6.12m)$$

$$A_{14} = \left((1 - f_r)\left(\frac{Q}{d}\right) - T_M\right)(q_{r\vartheta} + q_{m\vartheta}) = Q^2 \left(\frac{(1-f_r)}{d} - \frac{k}{\gamma}\left(1 - \beta_\zeta\right)\right)\left(\frac{f_r \nu}{d} + (1 - f_r)\left(\frac{\gamma}{d}\right)\right) \quad (6.12n)$$

Where:

$$q_{r\vartheta} = f_r \left(\frac{Q}{d}\right) \nu \quad (6.12o)$$

$$q_{m\vartheta} = (1 - \omega)(1 - f_r)\left(\frac{Q}{d}\right) \gamma + \omega\, T_M\, \gamma = (1 - \omega)(1 - f_r)\left(\frac{Q}{d}\right) \gamma + \omega\, kQ\left(1 - \beta_{\zeta}\right) \quad (6.12p)$$

$$t_{\phi} = T_M - \left(\frac{Q}{d}(n - \phi + 1 - f_r)\right) = \left(\frac{kQ - \beta_{\zeta}\, dT}{\gamma}\right) - \left(\frac{Q}{d}(n - \phi + 1 - f_r)\right)$$
$$= \left(\frac{kQ}{\gamma}\left(1 - \beta_{\zeta}\right)\right) - \left(\frac{Q}{d}(n - \phi + 1 - f_r)\right) \quad (6.12q)$$

$$q_{\phi} = t_{\phi}\, \gamma \quad (6.12r)$$

Similarly, the annual holding cost of repairable stock at the vendor's side is written as:

$$H_{rep_v} = \frac{A_{15} h_{u_v}}{T} \tag{6.13}$$

Where:

$$A_{15} = \frac{1}{2}\left(\beta_\zeta dT\right)T_R = Q^2\left(\frac{\left(k\beta_\zeta\right)^2}{2v}\right) \tag{6.13a}$$

The annual holding cost of the serviceable stock at the buyer's side is written as:

$$H_{ser_b} = \frac{(\sum A_{16})h_b'}{T} \tag{6.14}$$

Where:

$$\sum A_{16} = kA_{16} = Q^2 \frac{k}{2d} \tag{6.14a}$$

In a similar manner, the annual holding cost of the repairable stock at the buyer's side is written as:

$$H_{rep_b} = \frac{A_{17} h_{u_b}}{T} \tag{6.15}$$

Where:

$$A_{17} = \frac{1}{2}\left(\beta_\zeta dT\right)T = Q^2 \frac{k^2 \beta_\zeta}{2d} \tag{6.15a}$$

The number of setups multiplied by the respective setup cost and divided by the cycle time gives the annual production (manufacturing and remanufacturing) setup cost at the vendor's side which is written as:

$$S = \frac{(m+\vartheta)S_r + (n+\vartheta)S_m}{T} \tag{6.16}$$

The number of orders multiplied by the batch ordering cost and divided by the cycle time yields the annual ordering cost at the buyer's side and it is written as:

$$O = \frac{kO_b}{T} \tag{6.17}$$

The unit production costs for manufacturing and remanufacturing a unit multiplied by the number of units manufactured or remanufactured, respectively, divided by the cycle time gives the annual production (manufacturing and remanufacturing) cost at the vendor's side and it is written as:

$$C_p = \frac{(\beta_\zeta dT)c_{re} + (kQ - \beta_\zeta dT)c_{mr}}{T} = \frac{kQ(\beta_\zeta c_{re} + (1-\beta_\zeta)c_{mr})}{T} = d(\beta_\zeta c_{re} + (1-\beta_\zeta)c_{mr}) \tag{6.18}$$

According to El Saadany et al. (2013) the annual investment in the design process to remanufacture a product a specific number of times and the annual cost of waste disposal respectively are:

$$C_{inv} = c_{inv}(1 - e^{-\theta\zeta}) \tag{6.19}$$

$$C_w = d(1 - \beta_\zeta)c_w \tag{6.20}$$

The annual cost of transportation be calculated as a fixed cost and variable component (Bozorgi et al., 2014; Bonney and Jaber, 2011). For the case of this study, the transportation between the vendor and the buyer is approximated as fixed cost per trip and can be written as:

$$C_t = \frac{d}{t_c}(1 + \beta_\zeta)F_t \tag{6.21}$$

A relationship between production and GHG emissions released from production has been presented in Jaber et al. (2013) that is based on Bogaschewsky (1995). Narita (2012) empirically verify a similar relationship for machine tools. As presented in Bazan et al. (2015b) the annual cost of GHG emissions from production (manufacturing and remanufacturing) is written as:

$$C_{GHG_e} = d\left(\left(1-\beta_\zeta\right)\left(a_p\gamma^2 - b_p\gamma + c_p\right) + \left(\beta_\zeta\right)\left(a_r\nu^2 - b_r\nu + c_r\right)\right)c_{ec} \tag{6.22}$$

Given that transportation of items occur between the vendor and the buyer, there are GHG emissions released by the supply chain system for each gallon of fuel consumed (Bonney and Jaber, 2011). The annual cost of GHG emissions from transportation is written as:

$$C_{GHG_t} = \frac{d}{t_c}\left(1+\beta_\zeta\right)g_t e_t c_{ec} \tag{6.23}$$

Exceeding certain emissions limits for GHG subject the system to an emissions penalty cost (Jaber et al., 2013) and the annual GHG emissions penalty cost is written as:

$$C_{GHG_p} = \sum_{i=1}^{x} Y_i c_{ep,i} \tag{6.24}$$

Where:

$$Y_i = 1, \text{ if } E > L_i \ (i = 1, 2, \dots, x), \text{ and } \qquad Y_i = 0, \text{ otherwise} \tag{6.24a}$$

A relationship between the material removal rate and the required energy used to remove the material is presented in Li and Kara (2011). A similar relationship regarding a continuous production process is also presented in Zanoni et al. (2014b). Adjusting the parameters from Li and Kara (2011) for the amounts of energy used for manufacturing and remanufacturing in terms of the production rate is presented in Bazan et al. (2015a, 2015b) is adopted for this model. The annual cost of energy used is written as:

$$C_N = d\left(\left(1-\beta_\zeta\right)\left(C_o' + \frac{C_1'}{\gamma}\right) + \left(\beta_\zeta\right)\left(C_o'' + \frac{C_1''}{\nu}\right)\right)c_{en} \tag{6.25}$$

The traditional supply chain optimization approach is to minimize the summation of the cost functions presented in Eqs. (6.12) – (6.21), which accounts for remanufacturing and waste disposal, but excludes the environmental costs from GHG emissions and energy. The sum of these of costs is given from Eqs. (6.22) – (6.25). The model in this chapter seeks to optimize the sum of all costs. The total annual cost can be written as:

$$TC = H_{ser_v} + H_{rep_v} + H_{ser_b} + H_{rep_b} + S + O + C_p + C_{inv} + C_w + C_t + C_{GHG_e} + C_{GHG_t} + C_{GHG_p} + C_N \tag{6.26}$$

With regards to the same supply chain governed under a VMI-CS coordination and referring to Figure 6.3 the following terms are defined.

The times to remanufacture and manufacture batches are given respectively as is:

$$t_R = \frac{R}{\nu} \tag{6.27}$$

$$t_M = \frac{Q}{\gamma} \tag{6.28}$$

Consequently, the time to remanufacture the collected stock and the time to manufacture the 'new' stock (in years) are given, respectively, as:

$$T_R = \frac{mR}{\nu} \tag{6.29}$$

$$T_M = \frac{nQ}{\gamma} \tag{6.30}$$

From El Saadany et al. (2013) and Bazan et al. (2015b) the remanufacturing batch size is given as:

$$R = \frac{\beta_\zeta nQ}{(1-\beta_\zeta)m} \tag{6.31}$$

Where,

$$\beta_\zeta = 1 - \left[\frac{(1-\beta)}{(1-\beta^{\zeta+1})}\right] \tag{6.32}$$

Similar to the supply chain model governed by the classical coordination, the annual holding costs for the model governed by VMI-CS coordination is calculated in similar manner to before by using areas B_i for $i = 1$ to 10 as per Figures 6.3. Accordingly, the annual holding cost of the serviceable stock at the vendor's side is given as:

$$H_{ser_v} = \frac{(\sum B_1 + \sum B_2)h'_v}{T} \tag{6.33}$$

Where:

$$\sum B_1 = mB_1 = \frac{mR^2}{2\nu} \tag{6.33a}$$

$$\sum B_2 = nB_2 = \frac{nQ^2}{2\gamma} \tag{6.33b}$$

The annual holding cost of the repairable stock at the vendor's side is given as:

$$H_{rep_v} = \frac{B_3 h_{u_v}}{T} \tag{6.34}$$

Where:

$$B_3 = \frac{1}{2}(\beta_\zeta dT)\left(\frac{\beta_\zeta dT}{\nu}\right) = Q^2 \frac{n^2 \beta_\zeta^2}{2\nu}\left(\frac{\beta_\zeta}{1-\beta_\zeta} + 1\right)^2 \tag{6.34a}$$

The annual holding cost of the serviceable stock at the buyer's side is given as:

$$H_{ser_b} = \frac{(\sum B_4 + \sum B_5 + \sum B_6 + \sum B_7 + \sum B_8 + B_9)h'_b}{T} \tag{6.35}$$

Where:

$$\sum B_4 = (m-1)B_4 = \frac{(m-1)}{2}(dt_R)(t_R) = \frac{(m-1)}{2} d \left(\frac{R}{\nu}\right)^2 = Q^2 \frac{(m-1)d}{2} \left(\frac{n}{m\nu}\right)^2 \left(\frac{\beta\zeta}{1-\beta\zeta}\right)^2 \quad (6.35a)$$

$$\sum B_5 = nB_5 = \frac{n}{2}(dt_M)(t_M) = \frac{1}{2} d \left(\frac{Q}{\gamma}\right)^2 = Q^2 \left(\frac{d}{2\gamma^2}\right) \quad (6.35b)$$

$$\sum B_6 = \frac{m(m-1)}{2} B_6 = \frac{m(m-1)}{2}(R - dt_R)(t_R) = Q^2 \frac{(m-1)n^2}{2m\nu} \left(1 - \frac{d}{\nu}\right) \left(\frac{\beta\zeta}{1-\beta\zeta}\right)^2 \quad (6.35c)$$

$$\sum B_7 = nB_7 = n\big((m-1)(R - dt_R) + (R - dt_M)\big)(t_M)$$

$$= Q^2 \left(\frac{n}{\gamma}\right) \left(\left(\left(\frac{n(m-1)}{m}\right) \left(1 - \frac{d}{\nu}\right) \left(\frac{\beta\zeta}{1-\beta\zeta}\right) \right) + \left(\left(\frac{n}{m}\right) \left(\frac{\beta\zeta}{1-\beta\zeta}\right) \right) - \left(\frac{d}{\gamma}\right) \right) \quad (6.35d)$$

$$\sum B_8 = \frac{n(n-1)}{2} B_8 = Q^2 \frac{n(n-1)}{2\gamma} \left(1 - \frac{d}{\gamma}\right) \quad (6.35e)$$

$$B_9 = \frac{1}{2}(mR + nQ - d(m-1)t_R - dnt_M) \left(\frac{(mR + nQ - d(m-1)t_R - dnt_M)}{d}\right)$$

$$= Q^2 \frac{n^2}{2d} \left(\left(\frac{\beta\zeta}{1-\beta\zeta}\right) + 1 - \frac{(m-1)d}{m\nu} \left(\frac{\beta\zeta}{1-\beta\zeta}\right) - \frac{d}{\gamma} \right)^2 \quad (6.35f)$$

The annual holding cost of the repairable stock at the buyer's side is given as:

$$H_{rep_b} = \frac{B_{10} h_{u_b}}{T} \quad (6.36)$$

Where:

$$B_{10} = \frac{1}{2}\left(\beta_\zeta dT\right)T = Q^2 \frac{n^2 \beta\zeta}{2d} \left(\frac{\beta\zeta}{1-\beta\zeta} + 1\right)^2 \quad (6.36a)$$

Given that there is no possible mixed batch of manufactured and remanufactured items, the annual production (manufacturing and remanufacturing) setup cost at the vendor's side is given as:

$$S = \frac{mS_r + nS_m}{T} \tag{6.37}$$

All remaining annual system costs are similar to those presented in the supply chain model governed by classical coordination. That is, Eqs. (6.17) to (6.25) hold. Similarly, the total system cost is the same as presented in Eq. (6.26).

With regards to the model governed by classical coordination, a Microsoft Visual Basic Macro sets $\zeta = 1$, and $k = 1$ and Q is computed using the Problem Solver Add-In built in Microsoft Excel such that the Total Cost of given in Eq. (6.26) is minimized. The Macro then increases the values for ζ and k (in nested loops) and re-computes the Total Cost. If the new Total Cost is less than the previous calculated value, the values of ζ and k, respectively, are increased and the process is repeated until the minimum Total Cost is found. For the VMI-CS coordination, the process is exactly the same, however, the Macro sets ζ, m, and n. The following section presents numerical examples and the results.

6.4 Numerical Example

For comparison purposes, the values of most parameters are identical to those in Bazan et al. (2015a) and described in Chapter 4. Energy usage and GHG emissions from remanufacturing are generally less than their respective manufacturing counterparts. Accordingly, the following input parameters have been used for the numerical examples in this section (Table 6.1 and Table 6.2).

Table 6.1 List of input parameters and their respective values

Parameter	Value	Units	Parameter	Value	Units
d	1000	[units/year]	c_w	6	[$/unit]
γ	2600	[units/year]	F_t	400	[$/truck]
ν	1300	[units/year]	t_c	80	[units/truck]
β	0.67		c_{ec}	18	[$/ton]
h_{p_v}	60	[$/unit/year]	a_p	0.0000003	[ton.year2/unit3]
h_{r_v}	30	[$/unit/year]	b_p	0.0012	[ton.year/unit2]

h_{u_v}	10	[$/unit/year]	c_p	1.4	[ton/unit]
h_{p_b}	40	[$/unit/year]	a_r	0.000000833	[ton.year2/unit3]
h_{r_b}	20	[$/unit/year]	b_r	0.002	[ton.year/unit2]
h_{u_b}	5	[$/unit/year]	c_r	1.4	[ton/unit]
S_m	1200	[$/setup]	g_t	375	[gallons/truck]
S_r	600	[$/setup]	e_t	0.01008414	[ton/gallon]
O_b	400	[$/order]	C_0'	57.96	[kWh/unit]
c_{m_r}	60	[$/unit]	C_1'	1855744	[KWh/year]
c_{r_e}	40	[$/unit]	C_0''	18.9	[kWh/unit]
c_{inv}	5000	[$/year]	C_1''	605110	[KWh/year]
θ	0.2		c_{en}	0.0928	[$/KWh]

Table 6.2 GHG emissions penalty scheme as given in Jaber et al. (2013)

i	Emission limit, L_i	Penalty charged, $C_{ep,i}$
1	$E \leq 220$	0
2	$220 \leq E < 330$	1000
3	$330 \leq E < 440$	2000
4	$440 \leq E < 550$	3000
5	$550 \leq E < 660$	4000
6	$E \geq 660$	5000

The values for Table 6.2 (Jaber et al., 2013) were arbitrarily set in line with the European Union Emissions Trading System. These penalties are suggested for a manufacturing process that has an optimal production rate of $\gamma = b_p/2a_p = 2000$ such that GHG emissions from the manufacturing process are minimized. Accounting for a remanufacturing process that is less automated in nature the GHG emission related parameters for the remanufacturing process are set such that $\nu = b_r/2a_r = 1200$. A similar adjustment has been made for the energy related parameters for the remanufacturing process. Tables 1 and 2 represent the input parameters for the base case of this study.

6.5 Results

The classical supply chain model was optimized for the traditional costs only, Eqs. (6.12) – (6.21), but the total cost computed accounting for the environmental costs Eq. (6.26). The optimal total system cost is $TC = \$138{,}595$ when $Q = 143.6$ units and $k = 3$ shipments, where the product is remanufactured $\zeta = 7$ times. This policy yields 320.5 tons of total GHG emissions (from all sources) per year and requires 583,204 kWh of energy for manufacturing and remanufacturing process. When optimizing collectively, that is minimizing the total cost given in Eq. (6.26), the optimal total system cost $TC = \$138{,}580$ with a batch of size $Q = 143.6$, and $k = 3$ shipments where the product is remanufactured $\zeta = 8$ times. This policy yields 320.3 tons of total GHG emissions (from all sources) per year and requires 581,843 kWh of energy for manufacturing and remanufacturing processes. With an insignificant change in the optimal decision variables and only a very small reduction in the total system cost, the total GHG emissions and energy used per year, it can be argued that a traditional optimization approach, as presented in the literature, may be sufficient. However, the most noticeable difference is that the number of times the product is remanufactured has increased from 7 to 8 times. That is, the life of the product has been extended by one period reducing the immediate need to dispose of items in landfill. Such a result should not be overlooked by management (the system decision makers).

Bazan et al. (2015a) showed that there is an optimal production rate for the production process that would minimize the total system cost as well. Taking this into account, the supply chain model has been investigated to determine the minimum total cost of the system for various manufacturing rates, varying from $\gamma = 1100$ to $\gamma = 5000$ units/year (note: the base case remanufacturing rate has been set constant at $\nu = 1300$). The results are shown in Figure 6.4. There is a constant, but small, decrease in the traditional supply chain cost components (the sum of Eqs. (6.12) to (6.21)). However, the environmental costs (the sum of Eqs. (6.22) to (6.25)), vary considerably with the change in the manufacturing rate. The highest total system cost is achieved when operating at lower manufacturing rates. As the production rate is increased, significant increases can be seen in the environmental and total costs, which are a result of a gradual increase in the emissions penalty tax that is applied. Interesting to note, is a range of near optimal manufacturing rates with the range $2500 \leq \gamma \leq 3200$ units/year where the total system cost do not exceed 1700 \$/year above the minimum total system cost. A similar behaviour is observed for the supply chain model governed by VMI-CS coordination where the same range of near optimality is also evident.

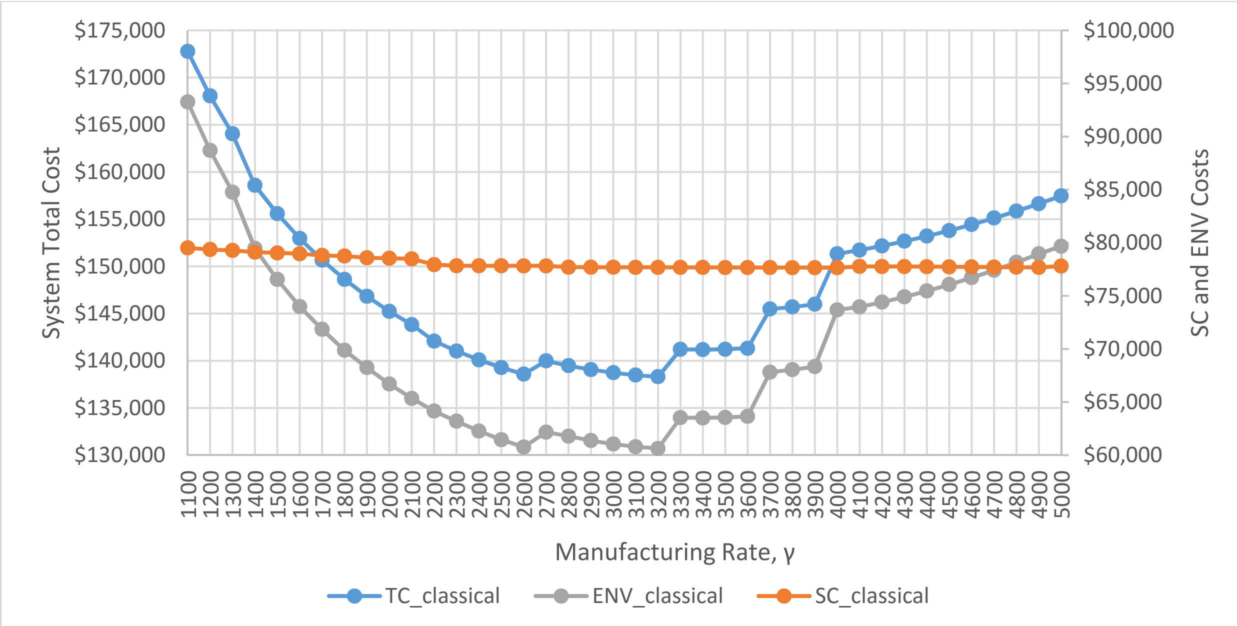

***Fig. 6.4** Total System, environmental and traditional supply chain costs for the model governed by classical coordination for the case where* $\nu = 1300$ *and* $1100 \leq \gamma \leq 5000$

Figure 6.5 shows the total system costs for the traditional and VMI-CS supply chain models and the optimal number of times an item can be remanufactured. For the complete range of γ the supply chain system governed by VMI-CS coordination is always slightly more economical. For a subset range of near optimal manufacturing rate, in the range $2800 \leq \gamma \leq 3200$, the number of times an item is remanufactured is of the same value, $\zeta = 7$, when governed by either coordination mechanism. However, for the remaining range of near optimal $2500 \leq \gamma \leq 2800$ the number of times a product is remanufactured in the classical coordination model is larger, $\zeta = 8$, than that of VMI-CS coordination model, $\zeta = 7$. The difference in total system costs between the two coordination mechanisms is roughly \$1900 per year, where VMI-CS is again more economical; however, the life of an item is reduced. If one is to operate under classical coordination and incur the additional \$1900 per year, this can be seen as a cost to extend the life of an item for one more remanufacturing period. The lowest number of times an item is remanufactured is $\zeta = 7$, which occurs for both classical and VMI-CS models, but is achieved at a longer range of manufacturing rates. As the manufacturing rate shifts to a value (slow or fast) outside the near optimal range, the number of times a product is remanufactured increases. The largest number of times a product is remanufactured is $\zeta = 13$, which occurs when the manufacturing rate is very low, $\gamma = 1100$.

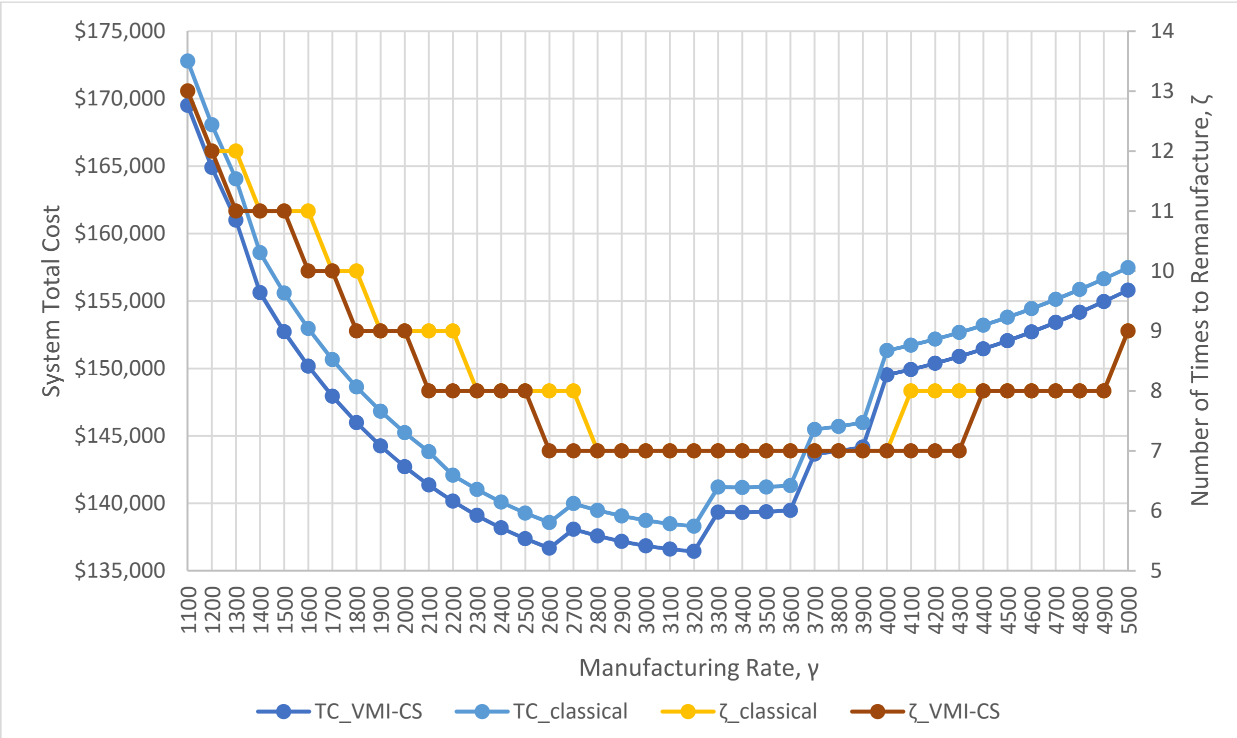

Fig. 6.5 *Total system cost and the number of times to extend the life of a product for the supply chain under classical and VMI-CS coordination*

Figure 6.6 shows the total cost of the supply chain governed by classical coordination when optimizing collectively (all fourteen cost functions given in Eq. (6.26)), as proposed by this paper, versus the same model where the traditional supply chain costs are the only ones optimized (i.e., minimizing Eqs. (6.12) – (6.21) then adding Eqs. (6.22) – (6.25) as previously discussed). The collective optimization approach yields lower total cost over the entire range of γ, $1100 \leq \gamma \leq 5000$. The savings are miniscule, but more evident for slow manufacturing rates. However, the result is significant when it comes to the extension of the life of the product. When optimizing the system using the traditional approach, the optimal number of times to remanufacture is constant at $\zeta = 7$, however, for slower and faster manufacturing rates the system pushes for more remanufacturing, which results in a reduction of the environmental costs (and impact) from energy usage and GHG emissions. A similar behaviour is found for the VMI-CS supply chain coordination model.

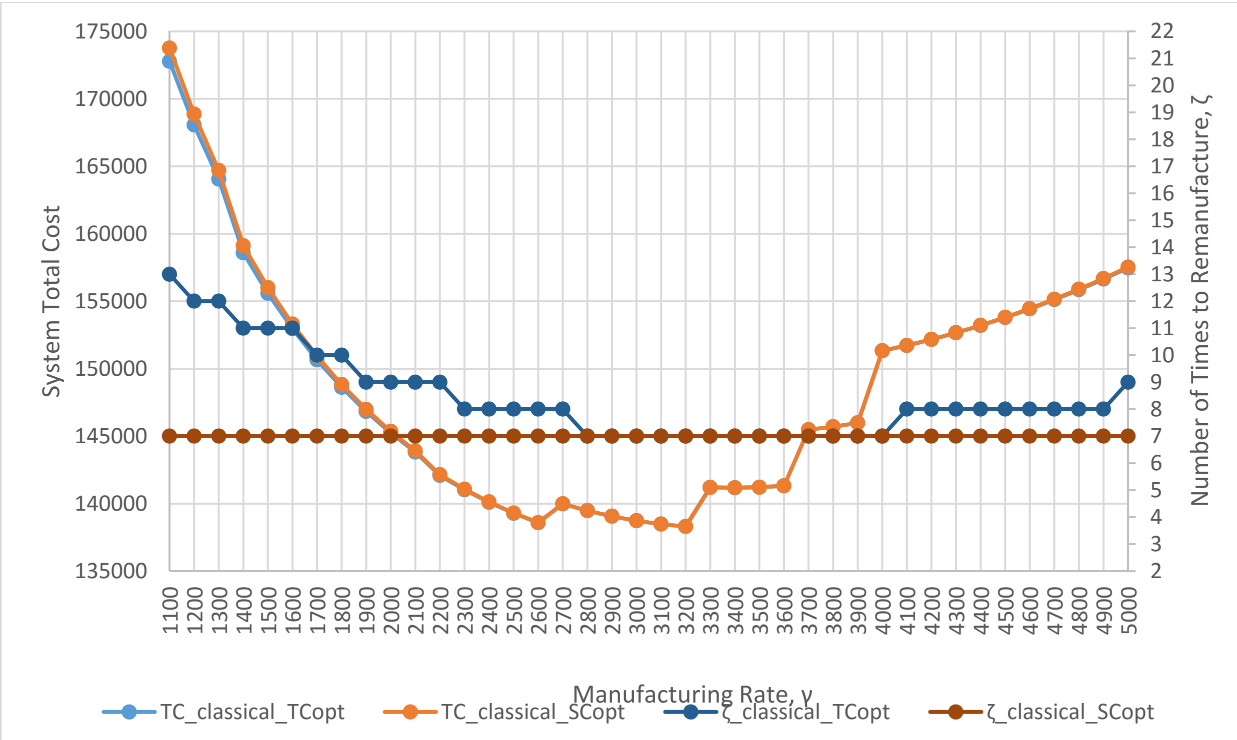

Fig. 6.6 *Total system cost for the supply chain governed by classical coordination when optimizing collectively versus when optimizing traditionally where TCopt means the model is optimized collectively, and SCopt means the model is optimized for traditional supply chain costs only*

The classical and VMI-CS supply chain models have been reinvestigated for the case when the remanufacturing rate is fast, $\nu = 2900$ units/year. Again, optimizing all cost functions collectively as opposed to optimizing only the traditional supply chain costs, yields lower total system cost, with a significant extension of the product's life at slow and fast manufacturing rates. This applies for both coordination mechanisms. As shown in Figure 6.7 the total cost function is smooth, as the system is penalized at the maximum GHG emissions penalty (from Table 6.2) over the complete range of γ (this is attributed to the fact that the remanufacturing rate is significantly above the optimal GHG emissions for remanufacturing). The total system costs for the classical and VMI-CS supply chain models are significantly higher than the case when the remanufacturing rate is very slow. For both models, the optimal manufacturing rate is significantly faster than the case when $\nu = 1300$, and the range of near optimal manufacturing rates at which the total system cost of the VMI-CS is 1900 $/year more than the optimal total system cost of the classical model is much larger, $2800 \leq \gamma \leq 4000$ (Figure 6.7). Again, for the complete range of γ, the supply chain governed by VMI-CS coordination always has lower total cost. This time, the reduction in cost is much more significant. For a smaller subset of this near optimal range where $3200 \leq \gamma \leq 3600$, the number of times a product can be remanufactured is the lowest, $\zeta = 4$. For the classical model the life of the product is extended by one more remanufacturing period, $\zeta = 5$. It should be noted, regardless of the coordination mechanism used, that the number of times to remanufacture is significantly low, when compared to the models when $\nu = 1300$.

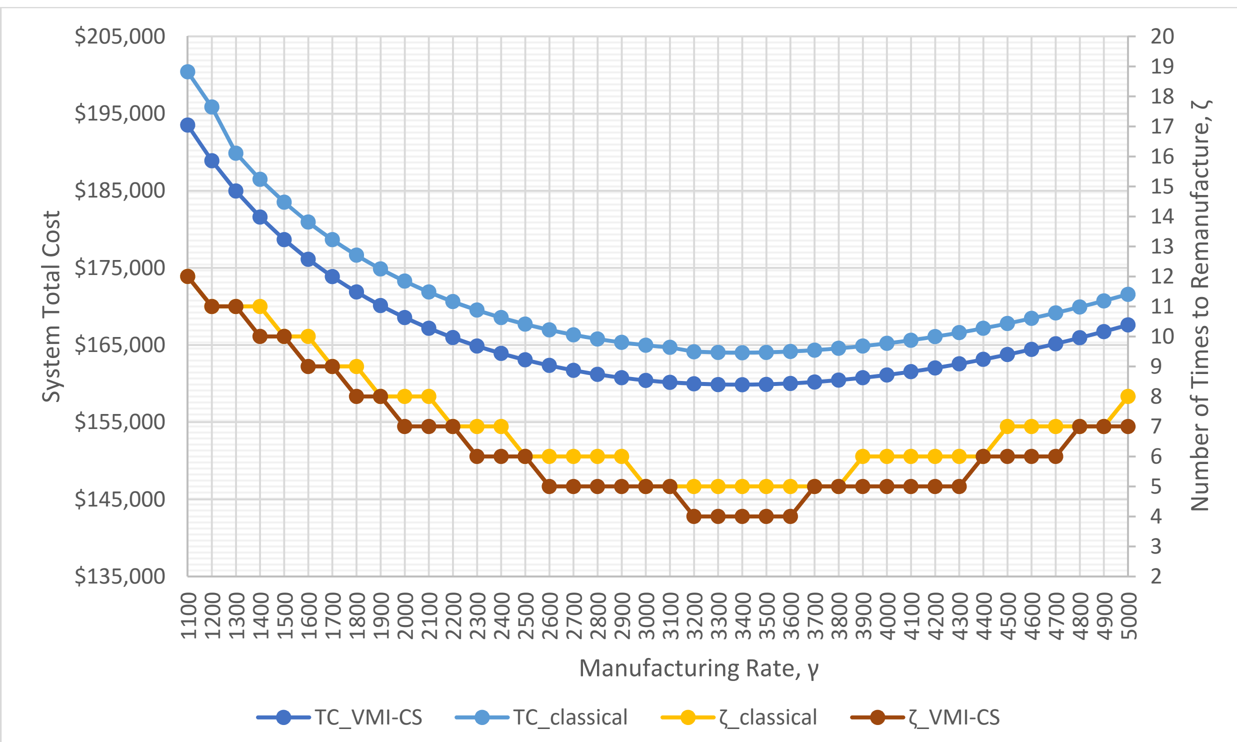

Fig. 6.7 *Total system costs and the number times a product is remanufactured for the supply chain governed by classical and VMI-CS coordination when* $\nu = 2900$

The collection of returned items that can be remanufactured affects the total system cost (Figure 6.8). As the collection of returned items increases, the traditional supply chain costs and the environmental costs decrease. This is valid for the classical and the VMI-CS models, whether the sum of all costs (inventory related and environmental cost) is optimised or just the sum of the inventory related (traditional) costs. As shown in Figure 6.8, the VMI-CS supply chain coordination model always operates at a lower total cost; however, the savings (difference between the classical and VMI-CS) reduce as the collection rate of used items increases; higher values of β. For lower and higher values of β the number of times the product is remanufactured is identical. However, for the range $0.4 \leq \beta \leq 0.7$ (excluding $\beta = 0.6$), the product life is extended by one more period with a classical coordination mechanism. Further results show that when β increases, GHG emissions and energy usage decrease regardless of the coordination mechanism. When optimizing the cost functions traditionally rather than collectively, the GHG emissions and energy usage for the collective optimization are less. If the model is governed by a classical coordination, the difference at a very low ($\beta \leq 0.1$) or a very high ($\beta \geq 0.9$) values of β is negligible. On the other hand, when the model is governed by VMI-CS coordination, the GHG emissions and energy usage values are identical for $\beta \leq 0.1$, but as β is increases, the savings from optimizing collectively also increase.

Fig. 6.8 *Total system costs and number of times to remanufacture at different values of β*

The annual investment in the design process facilitates the remanufacturing of products. For high annual design costs, the number of times to remanufacture a product is less and results in higher system costs. This behaviour is the same for both classical and VMI-CS models (Figure 6.9). Results in Figure 6.9 also show that the VMI-CS model is more economic for the full range of the annual investment in the design process, $2000 \leq c_{inv} \leq 20000$. If the models are optimized using the traditional approach, i.e. optimizing the sum of traditional costs in Eqs. (6.12) – (6.21), the number of times to remanufacture an item is reduced significantly when the annual investment becomes expensive. The reduction in the number of times to remanufacture increases as the annual investment in design increases, which increases the total system, energy, and GHG emissions costs. This suggests that it may be more appropriate to optimize the sum of the three mentioned costs (i.e., collectively) as proposed in both models of this chapter.

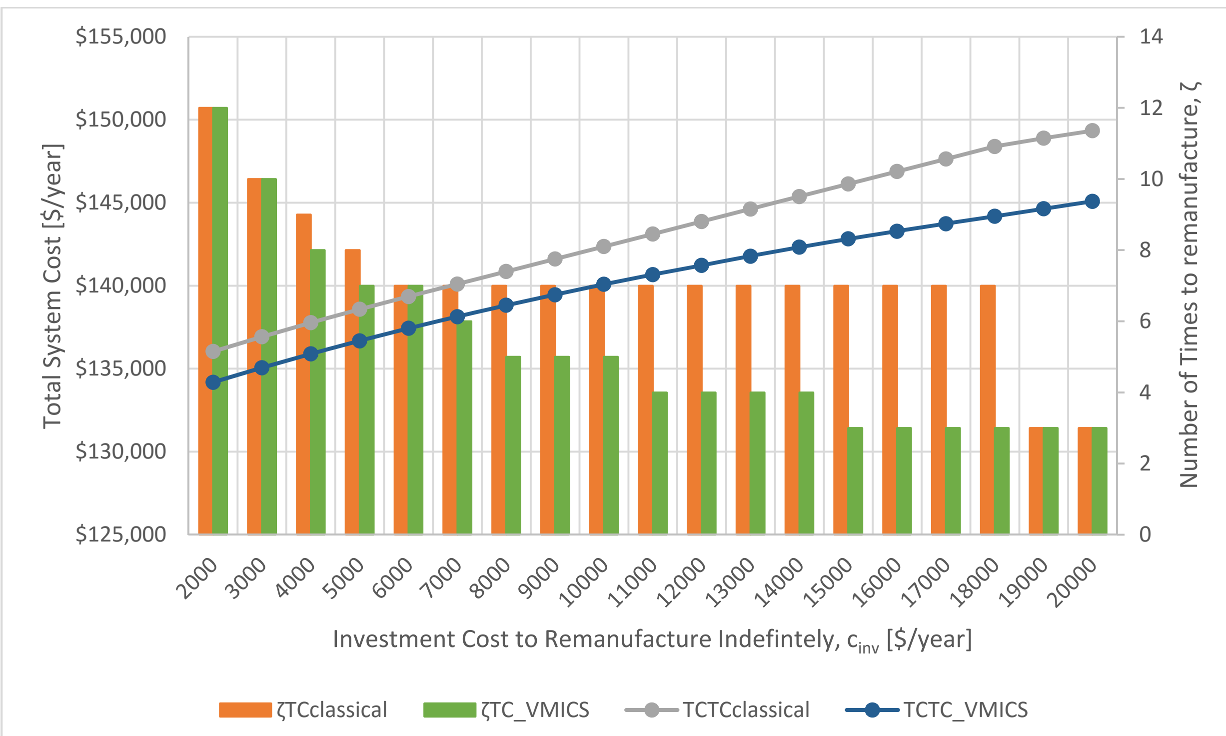

Figure 6.9 *Total system costs and number of times to remanufacture at different values of* c_{inv}

The tax per ton of GHG emissions, c_{ec}, undoubtedly would increase the overall system cost. Results showed that as c_{ec} was increased the number of times an item would be remanufactured would increase, but this only occurred when c_{ec} was increased to very large values $c_{ec} \geq 200$

\$/ton, and would not increase again until $c_{ec} \geq 500$ and $c_{ec} \geq 800$, respectively. These are considered astronomical values compared to the 18 \$/ton currently in effect (Jaber et al., 2013) indicating that the supply chain policies are not as sensitive to an increase in the carbon tax as it may be believed.

The combination of production rates, the availability of used items for remanufacturing, the product design costs and the coordination mechanism that governs the supply chain present the main criteria that can bring about a more environmentally responsible supply chain. Further analysis and discussion is presented in the following section.

6.6 Discussion

This section focuses on managerial insights and implications that extend beyond the presented results.

When discussing 'green' supply chains, it is almost implied that the model of concern is a closed-loop supply chain. Clearly, the common thought to protect the environment is to delay the disposal of the product, i.e. extend its life by as much as possible. However, the misleading step into considering a closed-loop supply chain model as 'green' is the inability of these models to account for the environmental costs beyond a mere estimate. In the proposed model, there are 14 cost components (see Section 6.3) of which the first ten represent the traditional cost components of a closed-loop supply chain system. While waste disposal costs are included in these ten traditional cost components, and the suggestion of reducing waste will reduce system costs, this may be misleading as the system may not necessarily be more environmentally friendly. The absence of the additional cost functions representing GHG emissions from production sources, transportation sources, associated carbon tax penalties and energy usage show that the suggested closed-loop models in the literature do not capture the true costs of the supply chain. As a result the inclusion of these costs (referred to as the environmental costs of the supply chain model) better portray the system costs and allow for more correct decision making and for more environmentally responsible decision making. It is important to be able to accurately measure (estimate) the emissions released and the energy used.

The presented results show that optimizing collectively (the sum of all costs) rather than traditionally (focus on setup, holding and disposal costs) is a better economic choice for a CLSC supply chain like the one considered here. However, for certain instances, such as the base-case presented, savings may not be seen significant enough by managers or decision makers of a supply chain to justify changes in their plans. They may also question the model and its associated costs required (from the modeller perspective) to develop the empirical formulas that accurately estimate the GHG emissions released and the energy used by the system. Their argument could be that the used traditional optimization is already operating at near optimal costs. This could be very misleading as such decision makers ignore that in addition to the small savings, the major benefit is that the number of times to remanufacture an item has increased, extending its life by at least another period. Furthermore, Figure 6 of the previous section shows clearly that at either high or low production rates the discrepancy in values for the optimal number of times to remanufacture increases – especially for the case when the manufacturing rate is relatively slow. Assuming a facility is operating at a manufacturing rate of $\gamma = 1100$ with a demand of $d = 1000$, where managers decide to optimize the system using the traditional approach , the product/item would be remanufactured six times less, $\zeta = 13$ to $\zeta = 7$. Clearly, this is associated not only with increased landfill waste, but also with a significant increase in the amount of core material and components that are required to manufacture new items to replace those disposed. Depleting resources, additional landfill, and biodegradability issues all arise. Quantifying the impact of these environmental factors is beyond the scope of this study, but cannot be ignored nonetheless.

For the VMI-CS model the results show a clear need to optimize collectively for all costs and not just optimize the traditional cost components as it would be less costly for the system. Optimizing all costs collectively becomes more prevalent when operating at slower and/or faster manufacturing rates. Figure 6.4 highlights that the environmental costs are very sensitive to the manufacturing rate, which makes it the leading driver of the total supply chain cost, either up or down. The general assumption that production (both manufacturing and remanufacturing) rates are greater than the demand rate will guarantee no shortages or stock-outs for the buyer, but the manager is now aware that speeding or slowing the production rate of the facility can significantly impact the system when they are optimized collectively, whereas when optimizing the sum of the traditional costs (setup, holding and waste disposal) the effect of production rate is minimal so it can go unnoticed. This merely highlights the importance of a manager to look beyond the system costs. Optimizing collectively, the sum of all costs, as proposed in the model does provide minute savings, but the environmental effects associated with some of the costs extend beyond these numbers and should not be overlooked or ignored.

Managers, however, may take advantage of a 'near optimal' manufacturing rate range, $2500 \leq \gamma \leq 3200$ as it provides flexibility in operating at rates where the total cost is relatively insensitive; i.e., it does not exceed 1700 $/year or approximately 1% of the total supply chain system cost. It is interesting that at faster remanufacturing rates, $\nu = 2900$, the manager's flexibility in setting an optimal policy increases; the new 'near optimal' manufacturing rate range is $2800 \leq \gamma \leq 4000$. The ranges for both cases are similar for the traditional and VMI-CS supply chain models. The increase in flexibility could be seen as beneficiary from the workshop floor level, but it should be cautioned that this increase in flexibility occurs at higher prices as the higher production rates (both manufacturing and remanufacturing) significantly increase GHG emissions released resulting in increased emissions cost and subjecting the system to higher carbon tax penalties, driving the costs further higher. Conversely, operating at higher production rates may be beneficial. Possibilities include freeing production capacity for other products or to lease capacity of the facility in general. As shown, speeding the remanufacturing rate speeds the manufacturing rate. In fact, adding a remanufacturing process to a two-level supply chain model (e.g., Bazan et al., 2015a) speeds the manufacturing rate for both supply chain coordination models. Optimal manufacturing rates for the classical and VMI-CS coordination can be seen at 3400 units/year well above those presented in Bazan et al. (2015a).

The type of coordination affects the performance of a supply chain. The results (Figure 6.5) show that the VMI-CS coordination model is always more economical than the classical coordination model. The results also show that the environmental costs are sensitive to the manufacturing rate, suggesting that the savings in the total cost from applying VMI-CS is in the traditional supply chain cost components. The downside however for the VMI-CS supply chain coordination model is that the number of times a product can be remanufactured is either less than or equivalent to that suggested by the classical supply chain coordination model. The question for a manager becomes: what cost is acceptable to extend the life of the product by one more period? For example, at an optimal manufacturing rate of $\gamma = 2600$ in Figure 6.5, the number of times to remanufacture is $\zeta = 7$ for VMI-CS and $\zeta = 8$ for classical coordination. If it remains under the VMI-CS coordination a manger may elect to reduce the manufacturing rate to $\gamma = 2500$ such that the optimal number of times to remanufacture is increased and the total system cost is only increased by $701 annually. This is a negligible cost to extend the life of the product. Reducing the cost more would result in increasing the cost more for the same number of times to remanufacture. However, when reduced below the near optimal range, the number of times to remanufacture is again increased extending the product life, however, costs are not near optimal. The increase in costs is attributed to slower manufacturing rate, which increases the environmental costs of GHG emissions released and energy used. In short, slightly slowing the manufacturing rate (within the near optimal range) extends the life of the product by one period at the expense of additional GHG emissions and energy usage. The following questions now arise: (1) which is more harmful to the environment now? and (2) which is more harmful in the long run? To avoid such a conflict it is suggested to switch from the VMI-CS to classical coordination and continue operating at the near optimal manufacturing rate of $\gamma = 2600$ (Figure 6.5). This decision extends the life of the product by one remanufacturing period with a slight reduction in GHG emissions and energy usage. This is a good scenario for the environment, however, at an additional annual cost of $1900. Is $1900 per year the cost of extending the life of the product by one period? It may not be necessary to switch policies to extend the life by one period. The results showed that one may continue with a VMI-CS, although near optimal, at an additional investment to remanufacture that costs way less than $1900. However, different factors may affect this decision. For example, if the product of concern is biodegradable or even just recyclable, which significantly reduces the total disposal cost, the investment to extend the product life may not be beneficiary. From a different angle, but with a similar conclusion, if the investment cost to remanufacture is significantly high due to the complexity of the product and/or the required technology associated with it, then extending the life of the product is also not beneficial. Design for X categories becomes important, such as designing for disassembly, remanufacturing, and environment can either drive costs up or down affecting the model decision parameters. Furthermore, a more economical annual investment cost for the design process suggests more remanufacturing and a reduction in the system costs. The investment in the design process may not necessarily yield direct benefits; for example, in Figure 9 for the classical model, when the annual investment cost is $18,000 ($20,000 - $2,000) cheaper the overall system savings would be $13,303 ($149,339 - $136,036). However, the product life is extended by 9 periods, $\Delta\zeta = 12 - 3 = 9$. This can be considered as an annual cost ($4,697) to extend an item's life 9 times with a reduction in both GHG emissions and energy usage.

Just as important as the design process for remanufacturing, is the availability of used items that for remanufacturing. Not having enough returned items does not make extending the life of product economical (Figure 6.8), even if the technology to extend the life of a product is available. Figure 6.8 shows that as more items are collected for recovery, the more significant are the savings. Thus, management should focus on how to increase the nominal collection rate β. However, two factors govern this decision. First, the quality of material and components used in building the product should be high. Second, the ease of return of used items by customers. In the current model, the end customers return their used items to the retailer. Incentives to do so could include trade-in value, e.g. exchange your old electronic device for a new one. Another incentive for customers could be to avoid landfill costs or the hassle of when disposing their own. Leasing options as those prevalent in the automobile industry also create a steady influx or returned products. An interesting and challenging problem to solve could be the possibility of remanufacturing a competitor's product. Collecting a competitor's product to disassemble and reuse of its components or just for disposal increases a firm's market share. This is not uncommon, for example, a computer is comprised of different components that are manufactured by different companies, some of which could be coming from the firm's suppliers.

Contrary to notion that legislative bodies tend to increase the tax on GHG emissions per ton to push firms and their supply chains to adopt more environmentally conscientious policies and practices, the developed models have shown that such a tax may not serve its purpose except for very large values making it unreasonable and impractical. In order to achieve an environmentally responsible policy, it is better to educate decision makers of the true costs and impact of bad environmental practices on a supply chain system and the society within which it operates.

Environmental awareness and pressures from stakeholders push supply chain decision makers to make economically sound decisions that are economically viable. The proposed models highlighted some of the environmental implications and consequences of decisions in an effort to ‘green’ supply chains.

6.7 Conclusion and Future Work

This chapter presented a two-level (Vendor-Buyer) closed-loop supply chain model of a manufacturer and retailer with the ability to remanufacture returned items. Two coordination mechanisms were considered. Three critical environmental issues were considered in the models: energy usage required for production, GHG emissions released from production processes and transportation activities and the extension of product life. Excess GHG emissions were subjected to a carbon tax penalty. Numerical examples were solved with results discussed to highlight managerial insights.

The results showed that a traditional optimization approach, which ignores environmental costs and focuses on setup, holding and waste disposal costs, suggested remanufacturing an item for less number of times than when optimising collectively (the sum of all costs: inventory related and environmental). This shortens the life of the product and increases waste, GHG emissions and energy usage. The environmental costs were also shown to be sensitive to changes in production (manufacturing and remanufacturing) rates. Optimizing traditional costs in many cases recommended very fast manufacturing rate, which results in higher GHG emissions.

Operating a supply chain according to VMI-CS coordinating mechanism has been shown to be more economical for the full range of the manufacturing rates considered and the annual investment in the design process. However, the downside is that the VMI-CS recommends remanufacturing an item for less number of times than the classical supply chain coordination model. A manger may then decide to stick with VMI-CS and operate near the optimal to extend the life of a product by one period. This will increase the GHG emissions and energy usage costs. Operating with a classical coordination may prove more environmentally responsible, but will come a cost higher than when operating off the optimal point for VMI-CS. It was also found that the availability of used items for remanufacturing significantly affect the costs for both models. This was suggested to be a primary focus for managers.

The models presented in this chapter gave a realistic glimpse of the primary factors affecting green supply chains. They represent a move in the direction of designing environmentally responsible supply chains. However, there are limitations to the work presented herein, and some future extensions may be considered. Environmental issues extend beyond GHG emissions and energy usage which were considered in this paper. For example, some production processes may depend on water consumption. Drought related areas will struggle with the costs of acquiring enough water, and areas of abundant water will also experience environmental and social issues as a result of the need for water. Chemical and toxic waste, other types of air emission, and noise pollution should also be considered in a future model. Putting a cost on such factors to be incorporated into a supply chain cost model would be a challenge to decision makers. However, it would be an interesting future research.

Managers are always confronted with conflicting objectives when operating a supply chain. For example, increasing the production rate decreases inventory related costs, but increases GHG emissions. If increasing emissions will reduce solid waste, is this environmentally friendly? Currently, all environmental issues have been represented as costs, and the primary objective is to reduce the total cost, which not necessary will reduce the environmental effects. Environmental issues should not be measured in terms of costs, but in terms of impact (like a scale). The associated cost should be one of many factors, but not the only one.

An overlooked area of concern in supply chain modeling is considering the complete life-cycle of a product. For a complete life-cycle analysis in a supply chain context the running cost and environmental impact of the product with the end customer should also be considered. Remanufactured products may be seen as good as new from a performance standpoint to the end customer (the product does the job), but not from an environmental impact view. For example, a computer monitor may still provide same picture quality or a fridge may function properly, but the energy used by the monitor and fridge may be more than compared to a newly manufactured monitor or fridge of the same design. Advances in design widen the environmental performance gap between new products and remanufactured ones. This may make remanufacture items less appealing, which may open a whole new direction for research.

Additionally, the proposed supply chain model considers a single product and only two players in the supply chain with one form of transportation. In a future work different modes of transportation and network structures should be considered. The current model shows that manufacturing and remanufacturing rates play an important huge in the environmental impact and some arguments suggest faster production to reduce costs and free capacity for other products. Can managers take advantages of operating at faster manufacturing rates by using the same facilities for multiple products? A multi-product supply chain model would be an extension that more resembles supply chains in the industry.

Chapter 7

SUMMARY, CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This chapter summarizes and concludes the work presented in this thesis. It also provides discussion and suggests future research directions. Elements from this chapter are from an accepted book chapter ("The Development and Analysis of Environmentally Responsible Supply Chain Models") in the upcoming editorial book "Green Supply Chain Management for Sustainable Business Practice", and Bazan et al. (2015c).

7.1 Thesis Summary

The review of Sasikumar and Kannan (2009) highlighted the increasing environmental concerns of stakeholders (managers, legislative bodies, customers, etc.) and how this has increased their attention to better understand reverse logistics and supply chain activities. They provided a comprehensive review of the literature to present two classification schemes and suggested possible research directions in reverse supply chains. Agrawal et al. (2015) corroborated the findings of Sasikumar and Kannan (2009) and emphasized the growing environmental concerns and government pressures, and sustainability issues. They also drew attention to the "well defined" costs in forward logistics and argued that they are not suitable for managing reverse chains. Similar to previous studies, Agrawal et al. (2015) provided a classification and categorized possible research directions. Govindan et al. (2015) extended their review to include closed-loop supply chain models. Similar to Sasikumar and Kannan (2009) and Agrawal et al. (2015), they concluded that mathematical models for reverse logistics and closed-loop supply chains should apply environmental and sustainable objectives. Brandenburg et al. (2014) also discussed that the modelling of reverse logistics and closed-loop supply chains lacks investigation and development in comparison to forward supply chains, where they wrote: "the understanding and review of mathematical models that focus on environmental or social factors" (Brandenburg et al., 2014), which serves the purpose of this thesis. Further, Brandenburg et al. (2014) discussed that there are very few studies from different industries whose findings have been overlooked by researchers. They also highlighted the importance of accounting for carbon emissions, energy and materials usage in transportation industries for example, and hazardous waste management in chemical or pharmaceutical companies.

Chapter 4 presented two models that consider energy used for production along with the greenhouse gases (GHG) emissions from production and transportation operations in a single-vendor (manufacturer) single-buyer system. It also considered a multi-level emission-taxing scheme. The first model of Chapter 4 considers a classical coordination policy, while the second considers a vendor-managed inventory with consignment stock (VMI-CS) agreement policy. Numerical examples for the two models were compared to outline managerial implications and insights. Energy usage has been found to be the main cost component for both models, suggesting that a reduction in energy usage is a priority. Key results showed that the VMI-CS model, over the different scenarios considered, allows a more economic operation of the system.

The responsible management of product return flows in production and inventory environments is a rapidly increasing requirement for companies. This can be attributed to economic, environmental and/or regulatory motivations. Mathematical modelling of such systems has assisted decision-making processes and provided a better understanding of the behaviour of such production and inventory environments. This thesis reviewed the literature on the modelling of reverse logistics inventory systems that are based on the economic order quantity and the joint economic lot size settings so as to systematically analyse the mathematics involved in capturing the main characteristics of related processes. The literature is surveyed and classified according to the specific issues faced and modelling assumptions. Special attention is given to environmental issues. There are indications of the need for the mathematics of reverse logistics models to follow current trends in 'greening' inventory and supply-chain models. The modelling of waste disposal, greenhouse-gas emissions and energy consumption during production is considered as the most pressing priority for the future of reverse logistics models.

Reverse logistics is inevitable in today's business environment with the most common reasons being product returns, incorrect product delivery, damaged products, and product exchange programs. The use and adoption of reverse logistics has increased with the start of product recalls, but the rise of e-commerce and insight into the positive environmental impact has elevated the formal use and sophistication of reverse logistics. There are many environmental issues that may arise from the production and transportation of products. The focus of this study is to evaluate supply chain environmental implications presented in a reverse logistic setting. These environmental contributions come with associated costs that can no longer be ignored in the mathematical modeling of reverse logistics.

Chapter 5 considered energy used for manufacturing and remanufacturing processes and the greenhouse gas emissions emitted from them. It also considered emissions from transportation activities along with penalty tax for exceeding emissions limits as per The European Union Emissions Trading System. The objective of the model in Chapter 5 is to minimize the total cost by solving for the optimal values of the manufacturing batch size, the numbers of manufacturing and remanufacturing batches per cycle, and the number of times to recover an item.

Numerical results showed that minimizing the sum of the traditional inventory and the environmental costs suggested less remanufacturing as opposed to focusing on solid waste disposal alone, with the latter being the focus of earlier studies in the literature. In addition, the results also showed the need to increase the collection of available used items that can be remanufactured.

Chapter 6 presented two models for a two-level closed-loop supply-chain model of a manufacturer and retailer with the ability to remanufacture items (classical and VMI-CS coordination). The three critical environmental issues of energy usage for production, GHG emissions from production processes and transportation activities (subject to a penalty tax), and the extension of product life were considered. Numerical results showed that the traditional optimization approach, which ignored environmental costs, suggested remanufacturing less, shortening the life of the product and increasing GHG emissions and energy usage. Environmental costs were shown to be sensitive to the production rates. Optimizing traditional costs in many cases recommended operating at high manufacturing rates, which results in higher GHG emissions. Results showed that the VMI-CS model was more economical for the full range of manufacturing rates considered, but this was not necessarily the more environmentally responsible choice. Different managerial decisions were discussed to further build upon the numerical results and provide alternative course of action for managers to take to be more environmentally conscious in their decision making.

7.2 Research Contributions

The main research contributions of this thesis can be summarized as follows:

1. A detailed literature review on environmental issues in supply chains with emphasis on reverse logistics inventory models has been presented
2. The mathematical models of Chapter 4 (classical and VMI-CS) are the first to simultaneously incorporate GHG emissions from, and energy usage by, different activities of a supply chain. Results from numerical examples and detailed sensitivity analysis to study the effects of energy and equipment technology, truck capacity, holding costs, and setup costs on the behaviour of the developed models.
3. The model of Chapter 5, to be the first in the literature, considered environmental effects in a reverse-logistics inventory context. The model considered remanufacturing as a form of product recovery. Environmental focus was given to three main issues: carbon emissions, energy and materials usage (solid waste). A heavy-duty off-road tire retreading and its oil sand customers in Northern Alberta, Canada, was used as an example.
4. Chapter 6 extended the model in Chapter 5 to consider a two level, rather than a single, closed-loop supply-chain model. Two coordination mechanisms between the vendor and the buyer (classical and VMI-CS) were investigated. Both models considered GHG emissions, a carbon tax penalty, energy usage, and solid waste. The two mathematical models of Chapter 6, to the author's knowledge, are the first to consider the mentioned environmental issues in a closed-loop supply-chain context.

Concluding, the thesis has addressed the stated objectives in Chapter 3 by:

- Analyzing supply chain systems to determine how they affect and impact the environment.
- Determining mathematical relationships to quantify the environmental and economic performance of a supply chain.

- Developing models that can quantitatively assess the environmental and economic performance of a supply chain.
- Optimizing the performance of the different supply chains developed in this thesis to help provide suggestions and insights to managers who have concerns about the trade-offs between profitability and being environmentally responsible.

The different models presented in this thesis provided an initial understanding of the primary factors affecting green supply chains. They represent a stepping stone in the direction of designing environmentally responsible supply chains. However, there are limitations to the work presented herein, and some future extensions may be considered.

7.3 Suggested Research Directions

The inventory models developed in this thesis represent may help, to some extent, a firm understand how to become more environmentally responsible. However, these models have limitations and more research is needed. One may ask, 'where do we go from here?' To answer this question, one must advance the research in the following areas: system analysis, environmental performance measures, and supply chain modeling (see Figure 7.1).

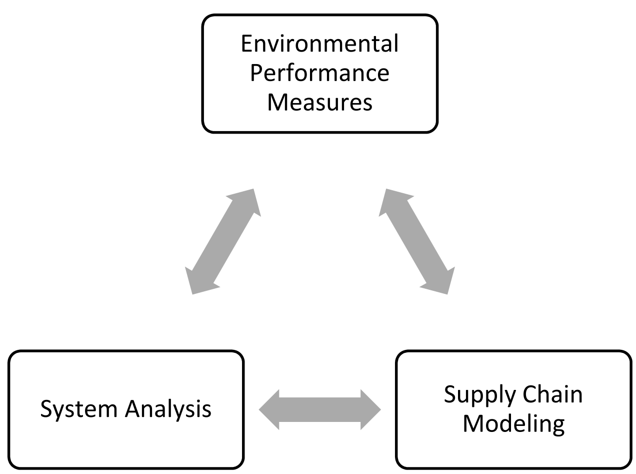

Figure 7.1 *The triangle of environmentally responsible supply chains*

These three areas are inter-related and feed on one another. For example, expanding the analysis of a system will result in developing appropriate performance metrics. Having this will result in a better modeling of supply chain systems that could feed back into system analysis and improved through insights and implications of the developed models. The remainder of this section will discuss each of these required advancements.

7.3.1 System Analysis

An important step before analyzing a system is defining its scope (Mumford, 1985). This helps system analysts in determining a set of outputs against whose performance could be measured. To do so an analyst must determine the system objective(s), consider the implications, and identify the limitations and constraints that may hinder achieving the set objective(s).

Defining the scope can also help in determining the participants. For example, does the study consider the extraction of raw materials, the manufacturing of components, sub-assemblies and assemblies, the distribution centers and warehouses involved, and/or the use of the product by the customer? Does the study consider the energy involved in manufacturing, fuel consumption in transportation, energy used for storage, greenhouse gases emitted from all activities, product disposal and the biodegradability (if any) of the material used in its production, etc.? These questions highlights the need to consider the type of industry and the product manufactured.

To illustrate, let us assume a general manufacturing case, where a manufacturer acquires materials and components to manufacture and assemble a single product, which is later delivered to retailers before being sold or leased to the end customer. At the end of the lease term or if the product has reached its end life, the end customer may return the product to the retailer or scrap the product (if applicable). A collected item will be inspected upon return, where the inspection decides whether a product could be reused as a whole (with some touch-ups) or that some of its parts, components or sub-assemblies are reused, repaired and then reused, remanufactured, recycled or disposed. Figure 7.2 depicts the processes and flow lines of the hypothesized system.

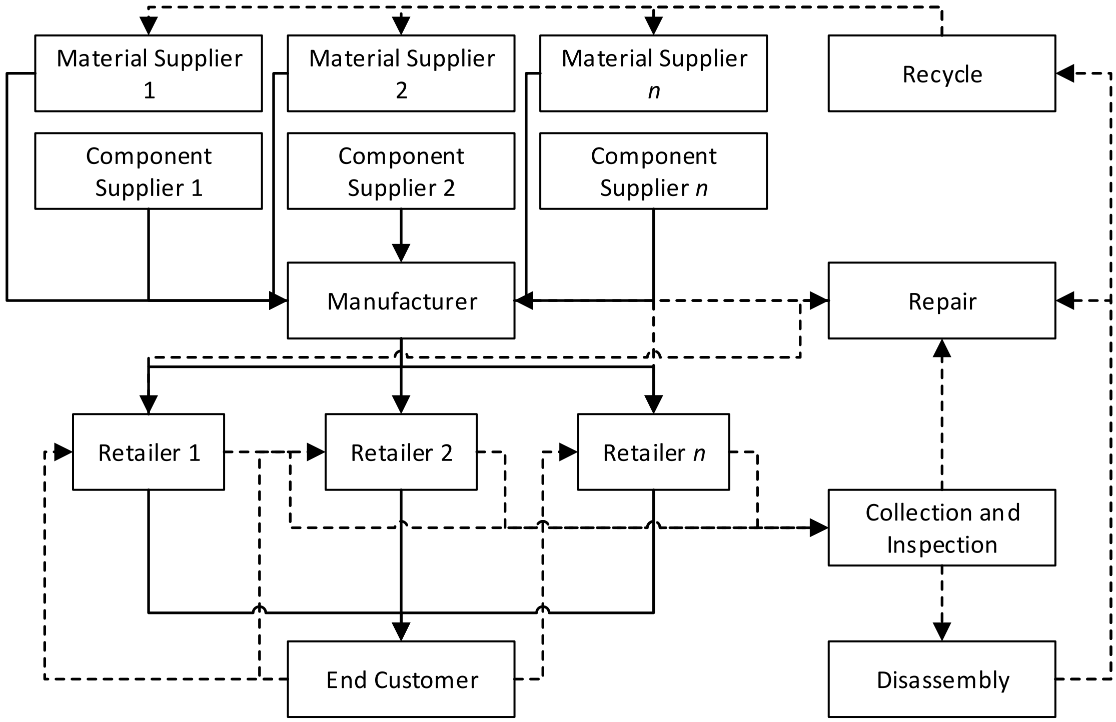

***Figure 7.2** An example for the forward and return flow of products, materials and components for a single manufactured product*

Performing a life-cycle assessment (LCA), for environmental analysis, of a product considered is a well-established procedure to build a picture of what occurs from extraction of raw material to production, to usage, to disposal, to recovery (Keoleian, 1993). Examples of use of LCA in the automotive industry, the chemical industry, the electronics industry, and the pulp and paper industry are found in National Research Council (US) Committee on Industrial Environmental Performance Metrics (1999). LCA helps in establishing performance measures and determining performance matrices. An interesting study for a future research is the work of Hagelaar and van der Vorst (2002) who suggested primary points to guide and applying LCA to supply chains. This could be a nice future extension if considered in the context of some of the models developed in this thesis.

Another tool that could facilitate the modeling of environmentally responsible supply chains is the framework proposed by Bonney and Jaber (2013). They suggested an input-output analysis approach that can be utilized to encompass the environmental factors associated with the supply chain. Such a task is daunting and requires efforts, but the input-output analysis provides a reasonable framework for a complicated task. Inputs including budgets, energy, materials, water, etc., which are transformed throughout the chain to desired outputs, the products, and undesired outputs which include waste and other environmental impacts. The input-output approach links the required inputs with the desired outputs and helps in developing responsible inventory and logistics systems.

Figure 7.3 is a simplified version of Figure 7.2 with inputs and outputs from each stage, where the output of one stage is the input of another. Assumptions in Figure 7.3 include: repaired items and recycled materials as good as new (which may not necessarily be the case for all industries/products), or that, e.g., a manufacturing sub-process may produce chemical waste in a facility while other sub-process do not in other facilities. Figure 7.3 suggests that energy use, GHG emissions and waste disposal are present in every facility. It also suggests that the amount of transportation involved is significant.

Numerous studies show a general hierarchy for recovery options of manufactured goods (Carter & Ellram, 1998; Steven, 2004; El Saadany, 2009). Mangers are faced with different options when operating and managing similar systems. The first option is to reduce the usage of required resources whether it be water, natural minerals and materials, fuel, etc. The second option is to prolong the life of a product and its reusability. The third option is to perform minor repairs. Other options include remanufacturing, refurbishing, recycling, disposal with energy recovery, and finally waste disposal in landfill sites. Figure 7.3 also implies that in order to achieve the best environmental results, the energy used to run the processes and the fuel consumed in transporting must be reduced to a minimum, and if possible to generate energy be from renewable sources and use green alternative fuel (if available) or hybrid transportation modes. The second focus is to prolong the useful life of a product with the customer. That is, perhaps, to have the technology and the option of gradual upgrades of a product so that a customer does feel the urge to dispose and replace.

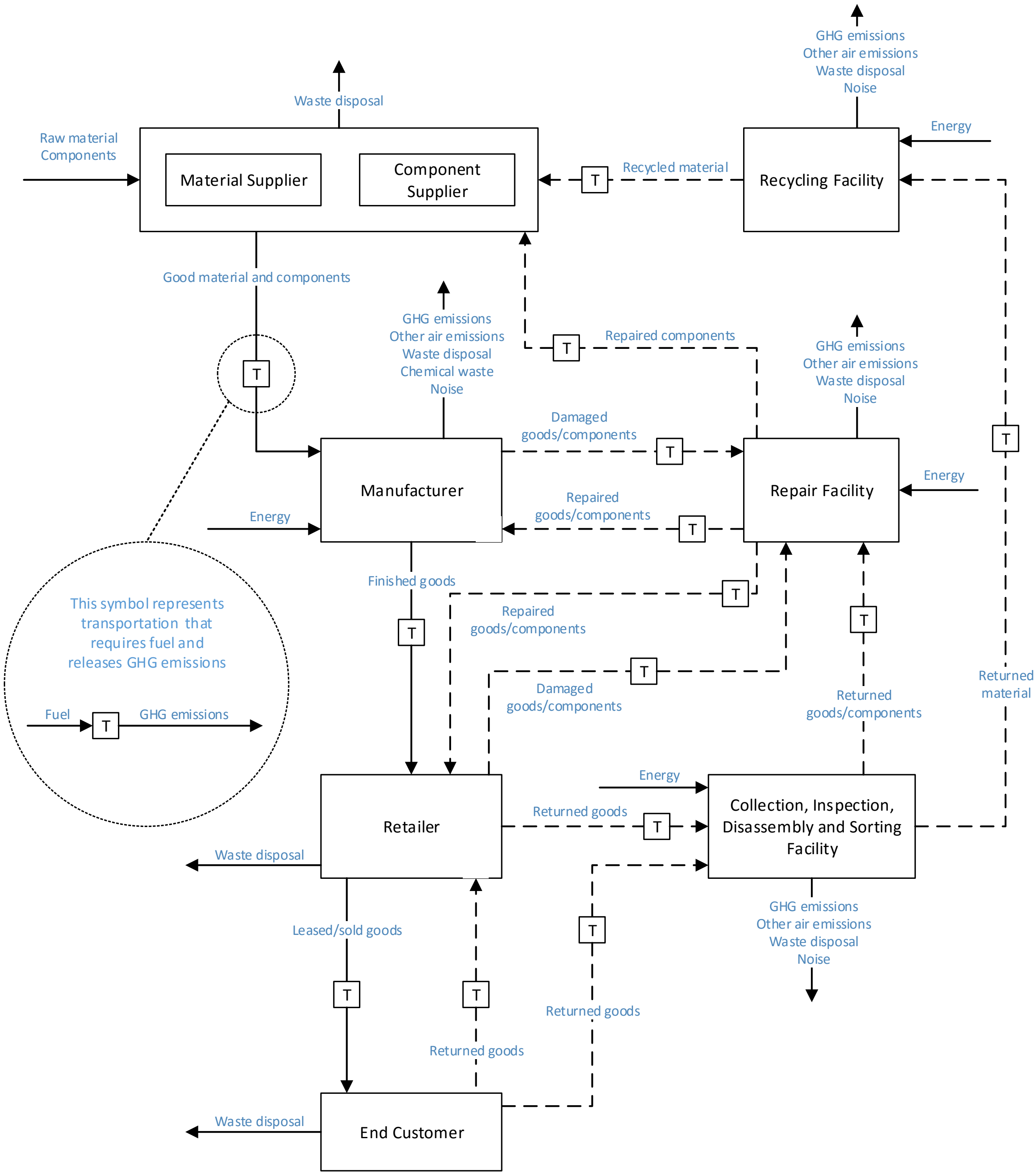

Figure 7.3 *An example input-output flowchart for a manufactured item with forward and return material flow*

The aforementioned example just briefly touches on environmental issues in supply chains and provide for the purpose of discussion. One limitation to the example presented example is that environmental impact that a product makes over its life while with the end customer has been ignored. For example, if this product was an automobile, GHG emissions and fuel consumption are major environmental issues. One must design for better fuel efficiency, alternative fuel and reduced or eliminated GHG emissions. A more detailed input-output analysis can lead to discussions on Design for Environment and Design for X categories. Design for Environment covers material selection which can help extend the of life of product and its biodegradability when disposed; Design for Manufacturing entails spending less time and energy for manufacturing, Design for Disassembly facilitates disassembly operations allowing minimal efforts for inspection, cleaning and repair operations (Kuo et al, 2001; Hauschild et al., 2004). The linking of these outputs to the inputs and the associated investment costs is necessary when modelling an environmental responsible system. There are huge challenges pertaining to cost accounting as they are not as sophisticated to capture the complex relationships presented.

The relationship between investment and projected results may be implemented to studied inventory and logistics systems. The combination of both LCA and the suggested input-output analysis framework could be seen as a strategic development that should be considered to tackle a problem like the one presented here. Developing such a framework is a complicated task. However, if developed, it can be used to investigate and analyse reverse logistics networks and closed-loop supply chains. A question remain: what complexity and level of detail is to be considered and at what cost?

An interesting study could be to analyze the supply chain models developed in this thesis using a unit cost rather than unit-time cost, another approach could be to investigate the developed models from a profit/revenue perspective and see if additional costs under specific situations could be absorbed.

Even though it is beyond the scope of this current study an important aspect of expanding the system analysis is to include social factors to complete the triple bottom line of economic, environmental and social issues to achieve sustainability in supply chains. Current social issues of immediate concerns include human health, safety, equity and quality of life (Hutchins and Sutherland, 2008). Identifying metrics to measure social issues in supply chains has been recently reviewed in Ahi and Searcy (2015). Keywords used in their review process were limited to metrics that included the words: ‘safety’, ‘welfare’ and/or ‘community’. Consequently, an interesting and direct extension to the models presented in this thesis would be to include health and safety incidents.

7.3.2 Environmental Performance Measures

To effectively combine LCA and input-output analysis to model and analyse environmentally responsible supply chains, performance measures become mandatory. Dr. Peter Drucker’s quote “what gets measured, gets managed” (Prusak, 2010) presented in Section 1.2 is significant and should resonate with those attempting to quantify the environmental impact of any activity. Generally, the approach is to quantify the costs associated with all activities and then optimize by minimizing the total cost associated with the processes in the supply chain considered. However, as previously discussed, the cost of certain effects cannot be accurately estimated. The cost of GHG emissions is assumed as a fixed cost per ton of emitted gases (Jaber et al., 2013; Zanoni et al., 2014a). They considered a penalty schedule for exceeding GHG emissions level as outlined by the European Union. Energy costs can be obtained per kilowatt hour used, but how much energy is exactly used by each operation? How much energy is used for storage items? What are the costs to repair and to remanufacture a used item, which may vary from one returned item to another depending on the damage caused or its level of deterioration? The majority of the associated costs are estimates; proposed penalty and charges imposed by legislative and governing bodies are mere judgment. The need for a more accurate performance measure other than just cost is deemed necessary.

As noted in Section 7.3.1, each industry will have its own set of environmental performance measures, with some commonalities (National Research Council (US) Committee on Industrial Environmental Performance Metrics, 1999). The Global Reporting Initiative (GRI) has a set of guidelines for sustainability reporting that include providing indicators for environmental factors.

However, these are merely guidelines and suggestions for businesses and organizations to consider and adapt to their specific industry (www.globalreporting.org). The work of El Saadany et al. (2011) discussed environmental performance measures for a supply chain. They use these performance measures to develop a model to investigate the performance of a supply chain considering economic, quality and environmental concerns. El Saadany et al. (2011) proposed an aggregated quality (performance) measure to capture different characterises of a product that reflect issues from the three categories: economic, environmental and social. They linked the proposed measure to a demand function and investigated how varying different elements of each category.

The main issue with developing performance measures is to establish measures that can be gathered timely, accurately and consistently so that appropriate and realistic targets can be achieved. Undoubtedly, improving a system's performance is beneficiary, but it may not be sufficient to only improve. Setting a realistic and acceptable target is critical. Planetary thresholds that should not be transgressed are proposed, global limits, to help avoid unacceptable environmental change (Rockström et al., 2009). However, such limits are not easily relatable to a specific supply chain. One interesting approach to investigate this issue is by revisiting the work of Jaber et al. (2004) in which an inventory system is modelled as a thermodynamic system. They suggest an entropy cost to account for hidden costs of the system which may account for environmental and social issues. As defined in the appendix of Jaber et al. (2004) the conservation of energy principle or energy balance, from the first law of thermodynamics, is: "Energy can be neither created nor destroyed; it can only change forms. The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process." Continuing along the analogy used to model the inventory system as a thermodynamics model we can identify an entropy level to achieve an equilibrium (in order to sustain the system) and translate this level into ceiling limits for environmental (and social) factors considered.

7.3.3 Supply Chain Modeling Implementation

The final stage is the combination of the results of system analysis and the suggested performance measures. To facilitate the task of mathematical modelling, some assumptions must be made to have a model resemble, with some reason, a real-life situation while keeping the mathematics trackable. Some assumptions serve the purpose of illustrating the behaviour of the model to draw some insights, but may fail to provide insights on some aspects of the developed model and therefore the results cannot be generalised. For example, the general assumption by many reverse logistics and closed-loop supply chain models that remanufactured products are as good as new. This may be the case for some products, but not for all. An overhauled engine, for example, will never be as efficient as a new one. A model must then account for different quality levels of a product and should consider different market segments for each quality level. (e.g., new and overhauled engines).

Subsequently, the comprehensive modelling of reverse logistics networks and closed-loop supply chains will not only expand the true realization of such networks and allow for economic and environmental benefits to be realized, but they open the door for quantifying other environmental efforts such as Design for the Environment and more generally Design for X categories (Kuo et al, 2001; Hauschild et al., 2004). The application of such design concepts can be easily presented by considering a simple product. Design for the Environment will include aspects such as selection of materials that may be readily recycled or biodegradable. Design for Manufacturing considers manufacturing in less time and such that less energy is used. Design for Disassembly allows for ease in disassembly and if coupled with Design for Serviceability then the components of longer shelf-life can be easily reused with minimal efforts in inspection and separation. Relationships between investment costs and the projected results may be implemented and their effect studied regarding inventory policies. It is wishful thinking that being environmentally friendly will be economical, but in order to validate this notion, one must quantify the need for developing a reverse logistics modelling beyond EOQ and repair costs is one step forward in achieving this.

In general, mathematical models of supply chains (based on the EOQ and joint economic lot size, JELS, settings) are of a single objective function (Jaber and Zolfaghari, 2008; Glock, 2012). The objective function is either to minimize cost or to maximize profit. When environmental issues are considered, which have different units of measure, a classic single-objective cost/profit function may not serve the desired purpose. Also, there may be conflicting objectives; for example, reducing the amount of energy consumed may result in higher GHG emissions or generating more solid waste. More appropriate is to model and optimise a multi-objective function (see for example Fonseca and Fleming, 1995; Van Veldhuizen and Lamont, 2000; Jin et al., 2001).

Determining the exact cost of environmental issues is a challenge and may not be possible without considerable interdisciplinary efforts. However, a simple non-classical modelling approach is suggested that is based on selected mathematical models from the literature. An illustrative example is presented and discussed in Appendix H.

The consideration of learning and forgetting in production and logistics activities are is a noteworthy addition as these factors affect the quality of both the worker and the product which, in turn may have social and environmental impacts, respectively. An increase in the number of defects that require rework means unnecessary energy usage, generation of GHG emissions and solid waste (e.g. scrap) disposal. An appealing extension would be to extend the work of Jaber and El Saadany (2011), which considers disassembling collected used items into components that are reused in production.

An interesting study would be to consider that manufactured and remanufactured items are produced in parallel not in series, as assumed in this thesis. This approach may result in a better utilization of shared resources and probably a better environmental performance. parallel production of manufacturing and remanufacturing is an intriguing one for its ability to utilize shared resources and possible reduce the environmental impact of the production process. Moreover, accounting for shortages and back-orders, online orders and e-commerce are interesting extensions to be considered in a future work. More daunting tasks would be to include multiple entities (manufacturer, supplier, retailer, etc.), tiers, and products. Finally, it should be emphasised that this work may be further extended considering other issues, like legislative requirements or marketing aspects that may have considerable impact on reverse logistics and, thus, may need to be considered in a mathematical modelling task.

7.4 Summary

The importance of developing environmentally responsible supply chain models is an issue that requires immediate attention. Natural resources are finite and current industrial practices are detrimental to the environment. This thesis summarized the current efforts in the inventory modeling of 'green' supply chain and showed a growing need for supply chain models that go beyond considering GHG emissions.

Recommendations presented in this thesis include addressing the need for appropriate environmental performance measures for supply chains and using these measures to expand on existing reverse logistic inventory models and closed-loop supply chain models covering economic and environmental aspects. Some environmental issues of immediate concern are the amounts of energy used, material used (and disposed of), and air emissions released to the environment.

Concluding, the integration of LCA with input-output analyses is suggested for a more comprehensive analysis of supply chains with the intent of relating system inputs with desired and undesired output. The issue of environmental performance measures is still in its infancy and requires more study and investigation to capture the true costs and the effects of supply chain activities on the environment. With the current research being at a relatively early stage, numerous challenges remain to quantify and measure environmental issues and impact. The complexity of modelling environmentally responsible supply chains and inventory systems recommends using multi-objective (not single) function. It is evident that in order to achieve sustainable operations and to attain progress in this regard, researchers and practitioners must collaborate to benefit from each other's skills. Such collaboration will result in mathematical models that resemble the real world more faithfully.

APPENDICES

Appendix A – Mathematical Review of Select RL Papers

A.1 Schrady (1967)

The model of Schrady (1967) determines the economic order quantities for procurement and repair batches in a simple system with two separate inventories, ready-for-issue (RFI) and non-ready-for-issue (NRFI) inventories where the NRFI are repaired. Basic assumptions include a deterministic model that considers no backorders.

Notations

Q_p	procurement quantity
Q_r	repair batch size
d	demand rate
r	recovery rate (measured as a percentage of d); $(1-r)$ is given as scrap rate
τ_p	procurement time
τ_r	repair time
A_P	fixed procurement cost per order
A_R	fixed repair batch induction cost per batch
h_1	RFI holding cost per unit per unit time
h_2	NRFI holding cost per unit per unit time
T	system cycle time, time between successive procurement quantity arrivals to RFI inventory
T_a	time period during which inductions are suspended and the overhaul and repair is simply accumulating NRFI items
n	number of inductions per cycle

Mathematical Model

The number of orders per cycle is given by:

$$n = \left(\frac{r}{1-r}\right)\frac{Q_P}{Q_R} \tag{A.1}$$

The cycle time is formulated as:

$$T = \frac{Q_P}{(1-r)d} \tag{A.2}$$

The total cost per cycle is given as the summation of the fixed order procurement cost multiplied by the number procurements per cycle (one in this case), the fixed induction cost multiplied by n inductions per cycle, the holding cost of RFI inventory, and the holding cost of NRFI inventory. That is the total cost per cycle can be given as:

$$TC_{cycle} = A_P + nA_R + h_1A_1 + h_2A_2 \tag{A.3}$$

where A_1 and A_2 are given as the areas under the curve that represent the average RFI and NRFI inventories, respectively. Dividing by the cycle time, the total cost per unit time is given as:

$$TC = \frac{A_P d(1-r)}{Q_P} + \frac{A_R r d}{Q_R} + \frac{h_1 r}{2}\left(Q_R + \left(\frac{1-r}{r}\right)Q_P\right) + \frac{h_2 r}{2}(Q_P + Q_R) \tag{A.4}$$

Differentiating the above equation with respect to the procurement quantity and repair batch size respectively, the optimal order quantities can be given as:

$$Q_P^* = \sqrt{\frac{2A_P d(1-r)}{h_1(1-r)+h_2 r}} \text{ and } Q_R^* = \sqrt{\frac{2A_R d}{h_1+h_2}} \qquad \text{(A.5), (A.6)}$$

It is evident that if the scrap rate is zero, i.e. $r = 1$, then there is no need to procure new items in the system.

Schrady (1967) used notations that slightly differ from the upcoming reviewed works. Table A.1 summarizes the differences and helps guide the reader. It should be noted that Schrady (1967) only assumed one repair cycle, that is $x' = nQ_P + Q_R$ whereas for Richter (1996a), Teunter (2001), and El Saadany et al. (2013) considered more than one, m, repair cycles, i.e., $x = nQ_P + mQ_R$. Also to be noted is that the model of Teunter (2001) considers the holding costs for manufacturing and recovery processes to be different.

***Table A.1**. Notation differences between Schrady (1967), Richter (1996b,1996a), Teunter (2001) and El Saadany et al. (2013)*

Definition	Schrady (1967)]	Richter (1996b, 1996a)	Teunter (2001)	El Saadany et al. (2013)
Lot size	$nQ_p + Q_r$	x	$MQ_m + RQ_r$	x
Repair/reuse/remanufacture percentage	r	β	β	β
Setup time for production/manufacturing	A_P	s	K_m	s
Setup time for repair/remanufacturing	A_R	r	K_r	r
Holding cost for serviceable stock	h_1	h	h_m, h_r	h
Holding cost for repairable stock	h_2	u	h_n	u

A.2 Richter (1996a)

With the underlying assumption that returned items may or may not be recoverable, the model of Richter (1996a) is an extension of the model of Schrady (1967). Of the assumptions considered is that the repair and use of the product is instantaneous, the repaired items are considered as-good-as-new, used items are collected at a defined repair rate and the remaining are considered waste and are disposed in landfill.

Notations

d	constant demand rate (units/unit time)
r	repair fixed cost
s	production fixed cost
b	manufacturing unit cost
k	repairing unit cost
e	disposal unit cost
h	holding cost per unit per unit time at shop 1 (where the production occurs)
u	holding cost per unit per unit time at shop 1 (where the repair occurs)
x	total lot size
T	collection interval (cycle time), $T = x/d$
α	disposal rate, $\alpha = 1 - \beta$
β	repair rate (equivalent to the recovery rate of Schrady, 1967)
n	number of production setups
m	number of repair setups
K_z	total cost of EOQ-related cost factors for time interval
K	total cost per time unit for the producer, $K = K_z/T$
R	linear production, waste disposal, and repair costs per unit time (non-EOQ related cost factors)
G	overall cost per time unit, $G = K + R$

Mathematical model

The total cost of the EOQ-related cost factors is the summation of the repair fixed cost, the production fixed cost, the holding cost at shop 1, and the holding cost at shop 2. That is:

$$K_z = (mr + ns) + \frac{h}{2d}\left(\frac{\alpha^2 x^2}{n} + \frac{\beta^2 x^2}{m}\right) + \frac{u\beta T x(m-1)}{2dm} \qquad \text{(A.7)}$$

Dividing by *T*, we get the total cost per time unit for the producer:

$$K = (mr + ns)\frac{d}{x} + \frac{x}{2}\left[h\left(\frac{\alpha^2}{n} + \frac{\beta^2}{m}\right) + u\beta + \frac{u\beta^2(m-1)}{m}\right]$$
(A.8)

Similarly, the linear production, waste disposal, and repair cost per unit time is given as:

$$R = d[\alpha(b + e) + (1 - \alpha)k] = d[\alpha(b + e - k) + k]$$
(A.9)

The overall cost per time unit is given as the summation of the EOQ and non-EOQ related costs:

$$G = K + R \qquad \text{(A.10)}$$

Depending on the disposal rate α, the optimal lot size that minimizes G is given by the following for the intervals of I (lower waste disposal rates), J, and L (higher waste disposal rates):

$$x(\alpha) = \sqrt{\frac{2ds}{\alpha^2 h + \beta u + \beta^2 u}}, \alpha \in I \quad \text{OR} \quad x(\alpha) = \sqrt{\frac{2d(r+s)}{(\alpha^2 + \beta^2)h + u\beta}}, \alpha \in J \quad \text{OR} \quad x(\alpha) = \sqrt{\frac{2dr}{\beta(\beta h + u)}}, \alpha \in L$$
(A.11)

The model of Richter shows that for low disposal rates, the fixed cost for repair has no effect on the total lot size, whereas for large waste disposal rates, the fixed production cost has no effect.

A.3 Teunter (2001)

Similar to Richter (1996a), Teunter (2001) extended the work of Schrady (1967) by generalizing the model, but different from Richter (1996a), Teunter (2001) has the disposal rate varying rather than being a constant rate and furthermore distinguishes between the holding cost rates for manufactured and recovered (remanufactured) items. Teunter also discussed that the quality of recovered items eventually, after a certain number of recovery processes, may not be the same as that of manufactured items and is used as a justification for the difference in holding costs, but does not reflect this in the modelling of the inventory system. Another important differentiation is that Teunter (2001) presented a simple closed form EOQ formulae as opposed to the complex formulae presented in Richter (1996a).

The objective is to find the optimal batch sizes for manufacturing and recovery batches, the number of each respective batch and the reuse rate.

Notations

λ	demand (continuous and deterministic)
g	return percentage ($0 < g < 1$)
β	reuse/recovery percentage($0 < \beta < 1$)
λg	items returned
$\lambda\beta$	items reused, where the units disposed are $\lambda(g - \beta)$
t	continuous time variable
c_m	cost of manufacturing an item
c_r	cost of recovering an item
c_d	cost for disposal of an item
K_m	setup cost for manufacturing
K_r	setup cost for recovery
h_n	holding cost for recoverable items
h_r	holding cost for recovered items
h_m	holding cost for manufactured items

Mathematical model

The total cost is given as the summation of both setup costs, the three holding costs, as well as the manufacturing, recovering and disposal costs. In their work, they showed that having M and R as even integers is always suboptimal and then later extend this to argue that optimal policies will occur either when $M = 1$ or $R = 1$.

For the case where $M = 1$ (one manufacturing batch) the total cost per time is given as:

$$TC_{M=1} = \frac{K_m\lambda(1-\beta)}{Q_m} + \frac{K_r\lambda\beta}{Q_r} + h_r\frac{1}{2}\beta Q_r + h_m\frac{1}{2}(1-\beta)Q_m + h_n\frac{1}{2}\left(\beta Q_r + \left(\beta - \frac{g-\beta}{1-\beta}\cdot\frac{\beta}{g}\right)Q_m\right)$$
$$+\lambda\big((1-\beta)c_m + \beta c_r + (g-\beta)c_d\big) \quad \text{(A.12)}$$

Note that Teunter (2001) uses *u* to represent β, we changed it to β to reduce confusion as there are too many notations. Setting the derivative of Eq. (A.12) to zero and solving gives the following optimal batch sizes:

$$Q_{m_{M=1}} = \sqrt{\frac{2K_m\lambda(1-\beta)}{h_n(1-\beta)+h_n\left(\beta-\frac{g-\beta}{1-\beta}\frac{\beta}{g}\right)}} \quad \text{(A.13)}$$

$$Q_{r_{M=1}} = \sqrt{\frac{2K_r\lambda}{h_r+h_n}} \quad \text{(A.14)}$$

Where the number of recovery batches is given by:

$$R = \frac{\beta}{1-\beta}\frac{Q_{m_{M=1}}}{Q_{r_{M=1}}}$$
(A.15)

For the case there $R = 1$ (one recovery batch), the total cost per time is given as:

$$TC_{R=1} = \frac{K_m\lambda(1-\beta)}{Q_m} + \frac{K_r\lambda\beta}{Q_r} + h_r\frac{1}{2}\beta Q_r + h_m\frac{1}{2}(1-\beta)Q_m + h_n\frac{1}{2}Q_r\frac{\beta}{g}$$
$$+\lambda\big((1-\beta)c_m + \beta c_r + (g-\beta)c_d\big) \quad \text{(A.16)}$$

Similarly, setting Eq. (16) to zero and solving gives the following optimal batch sizes:

$$Q_{m_{R=1}} = \sqrt{\frac{2K_m\lambda}{h_m}} \tag{A.17}$$

$$Q_{r_{R=1}} = \sqrt{\frac{2K_r\lambda g}{gh_r+h_n}} \tag{A.18}$$

Where the number of manufacturing batches is given by:

$$M = \frac{1-\beta}{\beta}\frac{Q_{r_{R=1}}}{Q_{m_{R=1}}} \tag{A.19}$$

The model of Teunter (2001) suggests that it is always optimal to either dispose of all returned items ($u = 0$) and have no recovery, or to recover all returned item (setting $g = \beta$).

A.4 El Saadany et al. (2013)

El Saadany et al. (2013) discussed the degradability of the material in a product as it is repaired, remanufactured, or recycled numerous times. They developed a mathematical expression that determines the number of times an item can be recovered. The main assumptions include a single product case, with unlimited storage capacity, infinite planning horizon, constant demand rate with no permissible shortages and zero lead time. The list of notations as provided in their work is given below.

Notations

ζ number of times an item is recovered

d demand rate (units per year)

β proportion of used units returned for recovery purposes when an item is recovered an indefinite number of times, $0 < \beta < 1$

α proportion of used units returned and disposed, $0 < \alpha < 1$

β_ζ proportion of used units returned for recovery purposes when an item is recovered a limited ζ number of times, $0 < \beta_\zeta < 1$

c_{Inv} remanufacturing investment cost over the life cycle of a product, \$ per year

θ investment increment factor, $0 \leq \theta < 1$

c_w disposal cost per unit, \$ per unit

Mathematical model

The disposal cost function can be written as:

$$C_w = c_w d\left(1 - \beta_\zeta\right) \quad \text{(A.20)}$$

Where the proportion of used units for recovery is given by:

$$\beta_\zeta = 1 - (1 - \beta)\left(\frac{1}{1-\beta^{\zeta+1}}\right) \quad \text{(A.21)}$$

The remanufacturing investment cost over the life cycle of a product is given by:

$$C_{Inv} = c_{Inv}\left(1 - e^{-\theta\zeta}\right) \quad \text{(A.22)}$$

The models of Richter (1997) and Teunter (2001) have been updated to account for the above where β is replaced with β_ζ. The consideration of the disposal cost and the investment cost in the models is seen as an important introduction from an environmental perspective as it drives the thinking process towards investment in increasing the number of times to repair a product extending the reuse and life of a product saving natural resources and minimizing landfill waste.

Appendix B – Quantitative Research Citing Schrady (1967)

Table B.1. *List of quantitative research citing Schrady (1967)*

#	Article Citation (APA format)
1	Schrady, D. A. (1967). A deterministic inventory model for reparable items. Naval Research Logistics Quarterly, 14(3), 391-398.
2	Freiheit, J. E. (1967). A continuous review model for the reparable item inventory system. Naval Postgraduate School Monterey CA.
3	Dollard, P. A. (1967). A periodic reparable-item inventory model (Doctoral dissertation, Monterey, California. US Naval Postgraduate School).
4	Allen, S. G., & D'Esopo, D. A. (1968). An ordering policy for repairable stock items. Operations Research, 16(3), 669-674.
5	A Dynamic Inventory Model with Delivery Lag and Repair. Defense Technical Information Center, 1969.
6	Simpson, V. P. (1970). An ordering model for recoverable stock items. AIIE Transactions, 2(4), 315-320.
7	Inventory Models with a Type of Dependent Demand and Forecasting, with an Application to Repair. Defense Technical Information Center, 1970.
8	Simon, R. M. (1971). Stationary properties of a two-echelon inventory model for low demand items. Operations Research, 19(3), 761-773.
9	Brown Jr, G. F., Lloyd, R. M., & Corcoran, T. M. (1971). Inventory models with forecasting and dependent demand. Management Science, 17(7), 498-499.
10	Quirk, D. J. (1972). A probabilistic event-step computer simulation of a repairable item inventory system. Naval Postgraduate School Monterey Calif.
11	Meyer, F. L. (1973). Analysis of the United States Navy Uniform Inventory Control Program and a proposed repair/procurement interface model. Naval Postgraduate School Monterey Calif.

#	Article Citation (APA format)
12	Haber, S. E., & Sitgreaves, R. (1975). An optimal inventory model for the intermediate echelon when repair is possible. Management Science, 21(6), 638-648.
13	Richards, F. R. (1976). A stochastic model of a repairable-item inventory system with attrition and random lead times. Operations Research, 24(1), 118-130.
14	Shanker, K. (1977). An Analysis of a Two-Echelon Inventory System for Recoverable Items (No. TR-341). Cornell Univ. Ithaca NY School Of Operations Research And Industrial Engineering.
15	Simpson, V. P. (1978). Optimum solution structure for a repairable inventory problem. Operations Research, 26(2), 270-281.
16	Nahmias, S., & Rivera, H. (1979). A deterministic model for a repairable item inventory system with a finite repair rate†. International Journal of Production Research, 17(3), 215-221.
17	Sherif, Y. S. (1982). Optimal maintenance schedules of systems subject to stochastic failure. Microelectronics Reliability, 22(1), 15-29.
18	Azoury, K. S. (1985). Bayes solution to dynamic inventory models under unknown demand distribution. Management Science, 31(9), 1150-1160.
19	Matta, K. F. (1985). A simulation model for repairable items/spare parts inventory systems. Computers & operations research, 12(4), 395-409.
20	Matta, K. F. (1986). Derivation of the cost equation of a dual replenishment inventory model with two order levels. Mathematical Modelling, 7(2), 273-284.
21	Albright, S. C., & Soni, A. (1988). Approximate steady-state distribution for a large repairable item inventory system. European Journal of Operational Research, 34(3), 351-361.
22	Park, B. G. (1988). Developing an inventory model for the Korean Air Force repairable item inventory. NAVAL POSTGRADUATE SCHOOL MONTEREY CA.
23	Lee, H. L., & Moinzadeh, K. (1989). A repairable item inventory system with diagnostic and repair service. European Journal of Operational Research, 40(2), 210-221.

#	Article Citation (APA format)
24	Schaefer, M. K. (1989). Replenishment policies for inventories of recoverable items with attrition. Omega, 17(3), 281-287.
25	Kumar, A., & Biumberg, H. (1991). A probabilistic model for a repairable mining equipment inventory system and procurement policy determination. International Journal of Surface Mining, Reclamation and Environment, 5(3), 117-121.
26	Mabini, M. C., Pintelon, L. M., & Gelders, L. F. (1992). EOQ type formulations for controlling repairable inventories. International Journal of Production Economics, 28(1), 21-33.
27	Chua, R. C., Scudder, G. D., & Hill, A. V. (1993). Batching policies for a repair shop with limited spares and finite capacity. European journal of operational research, 66(1), 135-147.
28	Richter, K. (1996). The EOQ repair and waste disposal model with variable setup numbers. European Journal of Operational Research, 95(2), 313-324.
29	Ashayeri, J., Heuts, R., Jansen, A., & Szczerba, B. (1996). Inventory management of repairable service parts for personal computers: A case study. International Journal of Operations & Production Management, 16(12), 74-97.
30	Dobos, I., & Richter, K. (2000). The integer EOQ repair and waste disposal model--further analysis. Central European Journal of Operations Research, 8(2).
31	Laan, E. A., & Teunter, R. H. (2000). Average Costs versus Net Present Value (No. ERS-2000-47-LIS). ERIM Report Series Research in Management.
32	Teunter, R. H. (2001). Economic ordering quantities for recoverable item inventory systems. Naval Research Logistics (NRL), 48(6), 484-495.
33	Teunter, R. H. (2001). A reverse logistics valuation method for inventory control. International Journal of Production Research, 39(9), 2023-2035.
34	Zhang, Y. (2001). Environmentally conscious supply chain, Master’s Thesis, Texas Tech University, USA

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35	Cho, D. I. (2001). Optimal stationary policy for a repairable item inventory problem. Canadian Journal of Administrative Sciences/Revue Canadienne des Sciences de l'Administration, 18(2), 130-143.
36	Cho, D. I. (2001). An approximation to a dynamic inventory model for repairable items. International Journal of Systems Science, 32(7), 879-888.
37	Wojanowski, R., Seelmann-Eggebert, R., & M. Schenk. (2001) Heuristics on reverse logistics." Proceedings of the 12th Annual Conference of the Production and Operations Management Society, March 30-April 2,2001, Orlando, Fl., USA
38	Dobos, I., & Richter, K. (2001). A production/recycling model with stationary demand and return rates-----Its title in Hungarian: Egy termelési/újrafelhasználási modell konstans keresleti és visszatérési ráta mellett.
39	Fleischmann, M., Kuik, R., & Dekker, R. (2002). Controlling inventories with stochastic item returns: A basic model. European journal of operational research, 138(1), 63-75.
40	Hu, T. L., Sheu, J. B., & Huang, K. H. (2002). A reverse logistics cost minimization model for the treatment of hazardous wastes. Transportation Research Part E: Logistics and Transportation Review, 38(6), 457-473.
41	Koh, S. G., Hwang, H., Sohn, K. I., & Ko, C. S. (2002). An optimal ordering and recovery policy for reusable items. Computers & Industrial Engineering, 43(1), 59-73.
42	Teunter, R. H., & Vlachos, D. (2002). On the necessity of a disposal option for returned items that can be remanufactured. International journal of production economics, 75(3), 257-266.
43	Teunter, R. H. (2002). Economic order quantities for stochastic discounted cost inventory systems with remanufacturing. International Journal of Logistics, 5(2), 161-175.
44	Mabini, M. C., & Christer, A. H. (2002). Controlling multi-indenture repairable inventories of multiple aircraft parts. Journal of the Operational Research Society, 1297-1307.
45	Dobos, I. (2002). The generalization of Schrady´ s model: a model with repair

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46	Mahadevan, B., Pyke, D. F., & Fleischmann, M. (2003). Periodic review, push inventory policies for remanufacturing. European Journal of Operational Research, 151(3), 536-551.
47	Teunter, R. (2004). Lot-sizing for inventory systems with product recovery. Computers & Industrial Engineering, 46(3), 431-441.
48	Dobos, I., & Richter, K. (2004). An extended production/recycling model with stationary demand and return rates. International Journal of Production Economics, 90(3), 311-323.
49	Richter, K., & Dobos, I. (2004). Production-inventory control in an EOQ-type reverse logistics system. In Supply chain management and reverse logistics (pp. 139-160). Springer Berlin Heidelberg.
50	Pati, R. K., Vrat, P., & Kumar, P. (2004). Cost optimisation model in recycled waste reverse logistics system. International Journal of Business Performance Management, 6(3), 245-261.
51	Hwang, H., Kim, Y. J., & Oh, Y. H. A deterministic production and inventory model for recycled material with Weibull deterioration.
52	Hwang, H., Choi, D. W., Ha, J. W., & Koh, S. G. Optimal inventory management policy for reusable items.
53	Sheu, J. B., Chou, Y. H., & Hu, C. C. (2005). An integrated logistics operational model for green-supply chain management. Transportation Research Part E: Logistics and Transportation Review, 41(4), 287-313.
54	Inderfurth, K., Lindner, G., & Rachaniotis, N. P. (2005). Lot sizing in a production system with rework and product deterioration. International Journal of Production Research, 43(7), 1355-1374.
55	Hedjar, R., Bounkhel, M., & Tadj, L. (2005). Receding horizon control of a hybrid production system with deteriorating items. Nonlinear Analysis: Theory, Methods & Applications, 63(3), 405-422.

#	Article Citation (APA format)
56	Kachitvichyanukul, V., Purintrapiban, U., & Utayopas, P. Inventory Level Of Recycled Material For Deteriorating Items Under LIFO Policy.
57	Kachitvichyanukul, V., Purintrapiban, U., & Utayopas, P. An Inventory Policy For Recycling System.
58	Dobos, I., & Richter, K. (2006). A production/recycling model with quality consideration. International Journal of Production Economics, 104(2), 571-579.
59	Tang, O., & Teunter, R. (2006). Economic lot scheduling problem with returns. Production and Operations Management, 15(4), 488-497.
60	van der Laan, E. A., & Teunter, R. H. (2006). Simple heuristics for push and pull remanufacturing policies. European Journal of Operational Research, 175(2), 1084-1102.
61	Konstantaras, I., & Papachristos, S. (2006). Lot-sizing for a single-product recovery system with backordering. International Journal of Production Research, 44(10), 2031-2045.
62	Oh, Y. H., & Hwang, H. (2006). Deterministic inventory model for recycling system. Journal of Intelligent Manufacturing, 17(4), 423-428.
63	Wee, H. M., Jonas, C. P., Su, L. H., & Wu, T. C. (2006). Optimal ordering and recovery policy for reusable items with shortages. In Simulated Evolution and Learning (pp. 284-291). Springer Berlin Heidelberg.
64	Oh, Y. for Reverse Logistics.
65	Li, Y., Chen, J., & Cai, X. (2007). Heuristic genetic algorithm for capacitated production planning problems with batch processing and remanufacturing. International Journal of Production Economics, 105(2), 301-317.
66	Buscher, U., & Lindner, G. (2007). Optimizing a production system with rework and equal sized batch shipments. Computers & Operations Research, 34(2), 515-535.
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68	Konstantaras, I., & Papachristos, S. (2007). Optimal policy and holding cost stability regions in a periodic review inventory system with manufacturing and remanufacturing options. European Journal of Operational Research, 178(2), 433-448.
69	Khawam, J., Hausman, W. H., & Cheng, D. W. (2007). Warranty Inventory Optimization for Hitachi Global Storage Technologies, Inc. Interfaces, 37(5), 455-471.
70	Teng, H. M., Wee, H. M., & Hsu, P. H. (2007). Optimal recycling and ordering policy with partial backordered shortage. In Computational Science and Its Applications–ICCSA 2007 (pp. 871-885). Springer Berlin Heidelberg.
71	Guo, F., & Zhang, T. (2007). The Optimized Inventory Control Based on Disposing Reverse Logistics in Set Volume with the Franchisers' Assistance. In International Conference on Transportation Engineering 2007 (pp. 558-563). ASCE.
72	Elsayed, M., M., A. (2007). Optimal control of some multi-item dynamical inventory models with deteriorating items.
73	Kaifu, Y. U. A. N., & Yang, G. A. O. EOQ models in hybrid system with goods shortage permission (http://www.seiofbluemountain.com/upload/product/200910/2007glhy15a5.pdf)
74	Chung, C. J., & Wee, H. M. (2008). Green-component life-cycle value on design and reverse manufacturing in semi-closed supply chain. International Journal of Production Economics, 113(2), 528-545.
75	Chung, S. L., Wee, H. M., & Yang, P. C. (2008). Optimal policy for a closed-loop supply chain inventory system with remanufacturing. Mathematical and Computer Modelling, 48(5), 867-881.
76	Rubio, S., & Corominas, A. (2008). Optimal manufacturing–remanufacturing policies in a lean production environment. Computers & Industrial Engineering, 55(1), 234-242.
77	Jaber, M. Y., & Rosen, M. A. (2008). The economic order quantity repair and waste disposal model with entropy cost. European Journal of Operational Research, 188(1), 109-120.

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78	El Saadany, A., & Jaber, M. Y. (2008). The EOQ repair and waste disposal model with switching costs. Computers & Industrial Engineering, 55(1), 219-233.
79	Qiaolun, G., Jianhua, J., & Tiegang, G. (2008). Pricing management for a closed-loop supply chain. Journal of Revenue & Pricing Management, 7(1), 45-60.
80	Gu, Q. L., & Ji, J. H. (2008). An integrated logistics operational model for Remanufacturing/Manufacturing system based on the consumer market. International Journal of Logistics Systems and Management, 4(1), 21-39.
81	Bu, X., & Xu, S. (2008, October). The profit model in reverse logistics under the different environment factors. In Service Operations and Logistics, and Informatics, 2008. IEEE/SOLI 2008. IEEE International Conference on (Vol. 1, pp. 1215-1220). IEEE.
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83	Nagar, P., & Srivastava, S. Inventory Level of Recycled Material for Deteriorating Items Under Lifo Policy1.
84	Schulz, T., & Ferretti, I. FEMM.
85	Li, C., Yang, X., & Zhang, Z. (2008, October). An Extended EOQ Model in Production-Recycling System. In Wireless Communications, Networking and Mobile Computing, 2008. WiCOM'08. 4th International Conference on (pp. 1-5). IEEE.
86	Yuan, K., & Gao, Y. (2008, October). Lot-Size Model for a Recovery System with Backordering and Disposal. In Wireless Communications, Networking and Mobile Computing, 2008. WiCOM'08. 4th International Conference on (pp. 1-4). IEEE.
87	Yuan, K., & Gao, Y. (2008, October). Manufacturing and Remanufacturing Lot-Size Model with Backordering and Disposal. In Wireless Communications, Networking and Mobile Computing, 2008. WiCOM'08. 4th International Conference on (pp. 1-4). IEEE.

#	Article Citation (APA format)
88	Fan, W., Ru, Y., Wang, Y., & Yao, C. (2008, October). Stochastic inventory control model with manufacturing and remanufacturing hybrid system. In Service Operations and Logistics, and Informatics, 2008. IEEE/SOLI 2008. IEEE International Conference on (Vol. 1, pp. 1268-1271). IEEE.
89	Srivastava, S., & Sharma, N. (2008). FIFO Controller Design Technique in JPEG 2000 Encoder Using Weibull Distribution. Proceedings of World Academy of Science: Engineering & Technology, 47.
90	Jaber, M. Y., & El Saadany, A. (2009). The production, remanufacture and waste disposal model with lost sales. International Journal of Production Economics, 120(1), 115-124.
91	Liu, N., Kim, Y., & Hwang, H. (2009). An optimal operating policy for the production system with rework. Computers & Industrial Engineering, 56(3), 874-887.
92	Wee, H. M., & Chung c, C. J. (2009). Optimising replenishment policy for an integrated production inventory deteriorating model considering green component-value design and remanufacturing. International Journal of Production Research, 47(5), 1343-1368.
93	Van Kooten, J. P., & Tan, T. (2009). The final order problem for repairable spare parts under condemnation. Journal of the Operational Research Society, 60(10), 1449-1461.
94	Omar, M., & Yeo, I. (2009). A model for a production–repair system under a time-varying demand process. International Journal of Production Economics, 119(1), 17-23.
95	Thoroe, L., Melski, A., & Schumann, M. (2009). The impact of RFID on management of returnable containers. Electronic Markets, 19(2-3), 115-124.
96	Hwang, H., Ko, Y. D., Yune, S. H., & Ko, C. S. (2009). A closed-loop recycling system with a minimum allowed quality level on returned products. International Journal of Services and Operations Management, 5(6), 758-773.
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99	Topcu, A. (2009). A heuristic approach based on golden section simulation-optimization for reconfigurable remanufacturing inventory space planning.
100	Khawam, J. H. (2010). Warranty inventory management and supplier decision models. Stanford University.
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103	Liu, G. F., & Yang, X. W. (2009, December). Multi-conditioned and capacitated production planning model for remanufacturing system. In Industrial Engineering and Engineering Management, 2009. IEEM 2009. IEEE International Conference on (pp. 1941-1945). IEEE.
104	Lee, Y. J. (2009). Integrated forward-reverse logistics system design: An empirical investigation (Doctoral dissertation, Washington State University).
105	Liu, X., Banerjee, A., & SL Kim, S.L.Models for retail pricing and customer return incentive for remanufacturing a product. In Proceedings of the POMS 20th Annual Conference, Orlando, Florida, USA, May (Vol. 1).(http://pomsmeetings.org/ConfProceedings/011/FullPapers/011-0851.pdf)
106	Chung, C. J., & Wee, H. M. (2009). An Integrated production inventory deteriorating model for short life-cycle green product remanufacturing, 6th Australia Conference on Life Cycle Assessment Suitability tools for a new climate, Melbourne, 16th-19th February 2009 (http://conference.alcas.asn.au/2009/Chung%20and%20Wee.pdf)
107	El Saadany, A., & Jaber, M. Y. (2010). A production/remanufacturing inventory model with price and quality dependant return rate. Computers & Industrial Engineering, 58(3), 352-362.

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108	Sana, S. S., & Chaudhuri, K. (2010). An EMQ model in an imperfect production process. International Journal of Systems Science, 41(6), 635-646.
109	Konstantaras, I., Skouri, K., & Jaber, M. Y. (2010). Lot sizing for a recoverable product with inspection and sorting. Computers & Industrial Engineering, 58(3), 452-462.
110	Konstantaras, I., & Skouri, K. (2010). Lot sizing for a single product recovery system with variable setup numbers. European Journal of Operational Research, 203(2), 326-335.
111	Yang, P. C., Wee, H. M., Chung, S. L., & Ho, P. C. (2010). Sequential and global optimization for a closed-loop deteriorating inventory supply chain. Mathematical and Computer Modelling, 52(1), 161-176.
112	Yuan, K. F., & Gao, Y. (2010). Inventory decision-making models for a closed-loop supply chain system. International Journal of Production Research, 48(20), 6155-6187.
113	Konstantaras, I. (2010). Optimal Control of Production and Remanufacturing in a Reverse Logistics Model with Backlogging. Mathematical Problems in Engineering, Article ID 320913, 19 pages (http://dx.doi.org/10.1155/2010/320913)
114	Johar, B. O. (2010). Inventory control issues in a disassembly line.
115	Kouchekian-Sabour, S. (2010). Reusability evaluation models in reverse logistics, Masters Theses, Ryerson University, Canada, Paper 1545.
116	Poles, R. (2010). System Dynamics modelling of closed loop supply chain systems for evaluating system improvement strategies, Doctoral dissertation, RMIT University, Australia
117	Muckstadt, J. A., & Sapra, A. Principles of Inventory Management.
118	Ying, Z., Tijun, F., Hong, Z., & Weixia, X. (2010, August). Economic ordering quantities for manufacturing/recovery inventory system with outsourcing. In Emergency Management and Management Sciences (ICEMMS), 2010 IEEE International Conference on (pp. 130-134). IEEE.
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120	Chung, C. J., & Wee, H. M. (2011). Short life-cycle deteriorating product remanufacturing in a green supply chain inventory control system. International Journal of Production Economics, 129(1), 195-203.
121	Jaber, M. Y., & El Saadany, A. (2011). An economic production and remanufacturing model with learning effects. International Journal of Production Economics, 131(1), 115-127.
122	El Saadany, A., & Jaber, M. Y. (2011). A production/remanufacture model with returns' subassemblies managed differently. International Journal of Production Economics, 133(1), 119-126.
123	El Saadany, A. M. A., Jaber, M. Y., & Bonney, M. (2011). Environmental performance measures for supply chains. Management Research Review, 34(11), 1202-1221.
124	Schulz, T. (2011). A new Silver–Meal based heuristic for the single-item dynamic lot sizing problem with returns and remanufacturing. International Journal of Production Research, 49(9), 2519-2533.
125	Alamri, A. A. (2011). Theory and methodology on the global optimal solution to a General Reverse Logistics Inventory Model for deteriorating items and time-varying rates. Computers & Industrial Engineering, 60(2), 236-247.
126	Teng, H. M., Hsu, P. H., Chiu, Y., & Wee, H. M. (2011). Optimal ordering decisions with returns and excess inventory. Applied Mathematics and Computation, 217(22), 9009-9018.
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134	Hou, R., & Lin, R. (2011, June). The integrated inventory model with shortage and missing orders based on reverse logistics. In Service Systems and Service Management (ICSSSM), 2011 8th International Conference on (pp. 1-5). IEEE.
135	Hung, C. Y. (2011). Optimal inventory polices in a closed-loop supply chain with reworking and remanufacturin, Master's Thesis, National Taiwan University of Science and Technology, Taiwan
136	Chang, Y. J., Chen, S. C., & Hsu, P. Y. (2011, August). A Search Algorithm for Solving the Economic Lot Scheduling Problem with Returns under the Basic Period Approach. In Management and Service Science (MASS), 2011 International Conference on (pp. 1-4). IEEE.
137	Dobos, I. (2001). Optimal inventory strategies for EOQ-type reverse logistics systems---------Its title in Hungarian: Optimális készletezési stratégiák a reverz logisztika optimális tételnagyság modelljeiben----.
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139	Widyadana, G. A., & Wee, H. M. (2012). An economic production quantity model for deteriorating items with multiple production setups and rework. International Journal of Production Economics, 138(1), 62-67.
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Appendix C – Classifications of the Cluster of RL Inventory Models based on EOQ/JELS

Table C1. Summary of Inventory Model Type

Article	Model Type	Objective	Modeling Parameters	Decision Variables
Schrady (1967)	- EOQ - Linear	Single objective	Deterministic	1. Procurement batch quantity 2. Repair batch quantity
Richter (1996a, 1996b)	- EOQ - Linear	Single objective	Deterministic	1. Total lot size
Richter (1997)	- EOQ - Linear	Single objective	Deterministic	1. Lot size 2. Number of repair lots 3. Number of production lots
Teunter (2001)	- EOQ - Linear	Single objective	Deterministic	1. Manufacturing batch size 2. Repair batch size 3. Number of repair batches 4. Number of manufacturing batches 5. Reuse rate
Teunter (2002)	- EOQ - Linear	Single objective	Stochastic	1. Manufacturing batch size 2. Repair batch size
Dobos and Richter (2003)	- EOQ - Linear	Single objective	Deterministic	1. Marginal use rate 2. Marginal buy-back rate 3. Production lot size 4. Recycling lot size 5. Time interval to recycle 6. Time to interval to produce
Dobos and Richter (2004)	- EOQ - Linear	Single objective	Deterministic	1. Marginal use rate 2. Marginal buy-back rate

Article	Model Type	Objective	Modeling Parameters	Decision Variables
				3. Production lot size 4. Recycling lot size 5. Time interval to recycle 6. Time to interval to produce 7. Number of production lots 8. Number of recycling lots
Teunter (2004)	- EOQ - Linear	Single objective	Deterministic	1. Manufacturing batch size 2. Repair batch size
Dobos and Richter (2006)	- EOQ - Linear	Single objective	Deterministic	1. Marginal use rate 2. Marginal buy-back rate 3. Production lot size 4. Recycling lot size 5. Time interval to recycle 6. Time to interval to produce 7. Number of production lots 8. Number of recycling lots
El Saadany and Jaber (2008)	- EOQ - Linear	Single objective	Deterministic	1. Total lot size
Jaber and El Saadany (2009)	- EOQ - Linear	Single objective	Deterministic	1. Number of production cycles 2. Number of remanufacturing cycles 3. Collection percentage of newly produced items 4. Collection percentage of remanufactured items
El Saadany and Jaber (2010)	- EOQ - Linear	Single objective	Deterministic	1. Purchasing price of returned items 2. Acceptance quality level

Article	Model Type	Objective	Modeling Parameters	Decision Variables
Jaber and El Saadany (2011)	- EOQ - Linear	Single objective	Deterministic	1. Number of production cycles 2. Number of remanufacturing cycles 3. Production lot size 4. Collection percentage of used items
El Saadany and Jaber (2011)	- Mixed integer	Single objective	Deterministic	1. Remanufactured items to total demand ratio 2. Ordering cost for subassembly (binary variable) 3. Remanufacturing cost of subassembly (binary variable)
El Saadany et al. (2013)	- EOQ - Linear	Single objective	Deterministic	1. Number of production batches 2. Number of remanufacturing batches 3. Proportion of used units returned for recovery

Table C2. Summary of inventory stock points

Article	Number of Stock Points	Type of Stock Points				
		New/Raw Material	Manufactured Item	Used Item	Remanufactured Item	Manufactured and Remanufactured Items
Schrady (1967)	2			X		X
Richter (1996a, 1996b)	2			X		X
Richter (1997)	2			X		X
Teunter (2001)	2			X		X
Teunter (2002)	2			X		X
Dobos and Richter (2003)	2		X			X
Dobos and Richter (2004)	2		X			X
Teunter (2004)	2			X		X
Dobos and Richter (2006)	2		X			X
El Saadany and Jaber (2008)	2			X		X
Jaber and El Saadany (2009)	2			X		X
El Saadany and Jaber (2010)	2			X		X
Jaber and El Saadany (2011)	2			X		X
El Saadany and Jaber (2011)	2			X		X
El Saadany et al. (2013)	2			X		X

Table C3. Summary of recovery activities

Article	Recovery Activities									Form of Recovery			
	Collection	Inspection	Separation	Disassembly	Repair	Refurbishment	Reuse	Remanufacturing	Recycling	Product Recovery	Material Recovery	Component Recovery	Energy Recovery
Schrady (1967)	X				X					X			
Richter (1996a, 1996b)	X				X					X			
Richter (1997)	X				X					X			
Teunter (2001)	X				X					X			
Teunter (2002)	X				X					X			
Dobos and Richter (2003)	X	X			X					X			
Dobos and Richter (2004)	X	X			X					X			
Teunter (2004)	X				X					X			

Article	Recovery Activities									Form of Recovery			
	Collection	Inspection	Separation	Disassembly	Repair	Refurbishment	Reuse	Remanufacturing	Recycling	Product Recovery	Material Recovery	Component Recovery	Energy Recovery
Dobos and Richter (2006)	X	X			X					X			
El Saadany and Jaber (2008)	X	X			X					X			
Jaber and El Saadany (2009)	X	X						X		X			
El Saadany and Jaber (2010)	X	X			X					X			
Jaber and El Saadany (2011)	X	X			X					X			

Article	Recovery Activities									Form of Recovery			
	Collection	Inspection	Separation	Disassembly	Repair	Refurbishment	Reuse	Remanufacturing	Recycling	Product Recovery	Material Recovery	Component Recovery	Energy Recovery
El Saadany and Jaber (2011)	X	X		X				X		X		X	
El Saadany et al. (2013)	X	X			X					X			

Appendix D – Specific Energy Calculations

It should be noted, the only way to determine the coefficients to calculate the total specific energy required for production is through an empirical study of the machine (Li and Kara, 2011). However, the following calculations can be used to estimate values for the required coefficients to illustrate the energy used by a machine.

Dahmus and Gutowski (2004) present a production machining centre where the total energy used per 1000 work hours is 160,996 KWh (both fixed and variable combined). Assuming a calendar year has 300 working days of 8 hours per day, the total number of work hours per year is $300 \times 8 = 2400$ hours. Hence, the total amount of energy per year is $160{,}996 \times \frac{2400}{1000} = 386{,}390.4$ KWh.

Given an assumed energy breakdown of 15% constant (fixed) energy and 85% variable energy (energy Case A in Table 4.3), the total constant energy per year is $386{,}390.4 \times 0.15 = 57{,}958.56$ KWh, and the total variable energy per year is $386{,}390.4 \times 0.85 = 328{,}431.84$ KWh.

C_0' represents the equivalent fixed energy per unit. Given the total demand per year assumed is 1,000 units, therefore $C_0' = \frac{57{,}958.56}{1000} = 57.95856$ KWh/unit.

The total amount of variable energy per unit is given by (C_1'/P). Given that the assumed production rate can be between 1,100 and 3,000 an arbitrary production rate of 1,100 will be used. Again the total demand per year assumed is 1,000 units, we have $(C_1'/P) = \frac{328{,}431.84}{1000} = 328.43184$ KWh/unit, and hence $C_1' = 328.43184 \times 1{,}100 = 361{,}275.024$ KWh/year.

Similarly, the values for C_0' and C_1' for the different energy breakdowns of energy Case B and Case C in Table 4.3 can be calculated.

Appendix E – Distance Matrix for Major Cities in Eastern North America

The following table shows rough distances between major cities in Eastern North America. The average of the distances listed below (292.2) is rounded up to 300 miles, which is assumed for this study.

City		Distance (miles)
New York City, NY	Buffalo, NY	373
New York City, NY	Washington, DC	226
New York City, NY	Boston, MA	216
New York City, NY	Philadelphia, PA	95
New York City, NY	Pittsburgh, PA	371
New York City, NY	Toronto, ON, Canada	491
New York City, NY	Baltimore, MD	188
New York City, NY	Montreal, QC, Canada	370
Detroit, MI	Pittsburgh, PA	286
Boston, MA	Philadelphia, PA	306

Appendix F – Calculation of Transportation Cost

Bozorgi et al. (2014) showed that the fixed transportation cost between two fixed locations of a truck to be \$200 per shipment. The truck is of capacity 500 units and the distance is 100 miles.

Assuming a linear relationship and a truck capacity of 80 units, then for a distance of 100 miles a truck shipment would cost $\frac{200\times80}{500} = 32$ \$/truck. For a distance of 300 miles, the transport cost of a truck is calculated at $\frac{32\times300}{100} = 96$ \$/truck.

For this study, the truck capacity is assumed to be either 40, 80, 120, or 160 (see section 4.2.3). It is understandable that for the various truck capacities, the cost of the truck and the associated fuel consumption may vary. For this study they are kept constant. At the time of this study diesel fuel prices are 4.17 \$/gallon (http://www.newyorkstategasprices.com). Therefore, for the assumed trip a total of $4.17 \times 75 = \$312.75$ is required for fuel. Hence, the total cost of transportation is given by the summation of the truck price per shipment and the associated fuel cost, i.e. $96 + 312.75 = \$408.75$ which is approximated to $\$400$ per truck per shipment for this study.

Appendix G – Derivation of Holding Costs in a Manufacturing-Remanufacturing Inventory Model

The following shows the derivation of the annual holding cost for serviceable and repairable stocks, i.e. Eqs. (5.1) and (5.2), respectively. In general, the holding cost of inventory per cycle is computed by calculating the average level of inventory per cycle multiplied by the associated inventory holding cost per item. In order to determine the annual holding cost of the inventory the inventory holding cost per cycle is divided by the cycle time.

From Figure 5.2 the average level of inventory for serviceable stock can be determined by calculating the area under the curve. Consequently the annual holding cost for serviceable stock can be given as:

$$H_1 = \frac{h_p\left(\frac{nQ^2}{2d} - \frac{n^2Q^2}{2\gamma} + \frac{Q^2}{2\gamma}n(n-1)\right) + h_r\left(\frac{mR^2}{2d} - \frac{m^2R^2}{2\nu} + \frac{R^2}{2\nu}m(m-1)\right)}{T}$$

Simplifying:

$$H_1 = \frac{\frac{nQ^2}{2}h_p\left(\frac{1}{d} - \frac{n}{\gamma} + \frac{(n-1)}{\gamma}\right) + \frac{mR^2}{2}h_r\left(\frac{1}{d} - \frac{m}{\nu} + \frac{(m-1)}{\nu}\right)}{T} = \frac{\frac{nQ^2}{2}h_p\left(\frac{1}{d} - \frac{1}{\gamma}\right) + \frac{mR^2}{2}h_r\left(\frac{1}{d} - \frac{1}{\nu}\right)}{T}$$

Substituting for the cycle time $T = \frac{nQ+mR}{d}$ and remanufacturing batch size $R = \frac{\beta_\zeta nQ}{(1-\beta_\zeta)m}$ (as discussed in the text) and simplifying, the annual holding cost for serviceable stock can be presented as a function of n, m and β_ζ, and it can be represented as:

$$H_1 = \frac{Q}{2}d\left[h_p\left(\frac{1}{d} - \frac{1}{\gamma}\right)(1-\beta_\zeta) + \frac{n}{m}h_r\left(\frac{1}{d} - \frac{1}{\nu}\right)\frac{\beta_\zeta^2}{(1-\beta_\zeta)^2}\right]$$

Substituting for actual proportion of items returned for recovery purposes when an item is recovered for a limited ζ number of times $\beta_\zeta = 1 - \left[\frac{(1-\beta)}{(1-\beta^{\zeta+1})}\right]$ and simplifying, the annual holding cost for serviceable stock as a function of the three decision variables n, m and ζ can be presented as:

$$H_1(n,m,\zeta) = \frac{Q}{2(1-\beta^{\zeta+1})}\left[h_p(1-\beta)\left(1-\frac{d}{\gamma}\right) + h_r\frac{n}{m}\frac{(\beta-\beta^{\zeta+1})^2}{(1-\beta)}\left(1-\frac{d}{\nu}\right)\right]$$

Similarly, from Figure 5.2 the area under the curve representing the returned inventory is equivalent to the average inventory of repairable stock. Multiplying by the corresponding holding cost and dividing by the cycle time will provide the annual holding cost for repairable stock and can be given as:

$$H_2 = \frac{h_u\left\{\frac{mR^2}{2\nu} + \frac{m(m-1)R^2}{2d} + \frac{\beta}{2d}(mR+nQ) - \frac{n\beta Q}{1-\beta}\left((m-1)\frac{R}{d} + \frac{R}{\nu}\right)\right\}}{T}$$

Repeating the same steps substituting $T = \frac{nQ+mR}{d}$, $R = \frac{\beta_\zeta nQ}{(1-\beta_\zeta)m}$ and $\beta_\zeta = 1 - \left[\frac{(1-\beta)}{(1-\beta^{\zeta+1})}\right]$ the annual holding cost for repairable stock can be given as a function of the three decision variables n, m and ζ can be presented as:

$$H_2(n,m,\zeta) = h_u\frac{nQ}{2}\left(\frac{\beta-\beta^{\zeta+1}}{1-\beta}\right)\left[\left(\frac{\beta-\beta^{\zeta+1}}{1-\beta^{\zeta+1}}\right)\frac{1}{m}\left(1-m-\frac{d}{\nu}\right)+1\right]$$

Appendix H - A Possible Approach to Modelling Environmentally Responsible Supply Chains

From the discussion in Chapter 7, it becomes apparent that a model that can capture the environmental factors present in reverse logistic systems is becoming inevitable. A new approach to the modelling of reverse logistics is suggested herein. Previous attempts treat the problem as a traditional inventory problem even though the inclusion of environmental factors no longer makes the problem a traditional one. This section seeks to present an example 'only' to illustrate the suggested approach: it merely formulates the problem, but there is no attempt to solve. The solution of the problem is left for additional research.

The suggested approach attempts to minimize multiple objectives, including costs and individual environmental factors alike. For the case of this illustration, the following environmental factors are considered: GHG emissions from production, energy usage for production, and disposal solid waste (unrepairable items). The concept of this model is based on the work of Richter (1996a). We extend this model to include the assumption of El Saadany et al. (2013) that an item can only be recovered for a limited number of times. For simplicity, additions from the Teunter (2001) model to account for different holding costs and the possibility of variable disposal rates will not be considered in this illustration. The model then includes two environmental additions suggested by Jaber et al. (2013) and Zanoni et al. (2014a) regarding the GHG emissions from a production process and the amount of energy used for production, respectively.

The rationale for the proposed approach is that real costs of some environmental factors are difficult to estimate; e.g. the costs of polluting air, soil and water tables to the public (Jaber, 2009). As a result, the model is now presented as a multi-variable multi-objective non-linear mixed integer programming problem. Such a problem can be considered a scalar function, but can be attempted as a multi-objective optimization problem. Since there is no single point that will simultaneously optimize all objectives at once, two fundamental approaches can be suggested: (1) scalarization and (2) Pareto. Not necessarily the most effective solution, one approach that is suggested in this paper for illustrative purposes and for its simplicity, is to have the objective function normalized as costs, GHG emissions, energy used and items disposed of are of different units. The importance of each factor is determined by a weight. Individual priorities for the costs and the environmental factors can be determined from the experience of managers, various stakeholders, and ultimately the decision makers involved. This problem is not discussed in this paper, but is rather left for future investigation.

The model considers three main cost categories: the EOQ related and non-related costs given in Eqs. (A.8) and (A.9) of Appendix A, respectively, as presented by Richter (1996a), as well as the investment cost associated with the repair and recovery of returned items given in Eq. (A.22) of Appendix A (El Saadany et al., 2013). It should be reminded that since El Saadany et al. (2013) showed that the β in Eqs. (A.8) and (A.9) of Appendix A has to be replaced with β_ζ , where ζ is the number of time to recover an item, is given in Eq. (A.21) of Appendix A.

The total number of items disposed as solid waste by the system, S_w, is computed as:

$$S_w = \alpha d \tag{H.1}$$

Where the proportion of used units returned and disposed, α, can be calculated as:

$$\alpha = 1 - \beta_\zeta = (1 - \beta)\left(\frac{1}{1-\beta^{\zeta+1}}\right) \tag{H.2}$$

From Jaber et al. (2013) the emissions generated from a production process is given in terms of the production rate as:

$$E = a_e P^2 - b_e P + c_e \tag{H.3}$$

Where:

- E GHG (CO_2) emissions generated per year (ton/year)
- a_e emissions function parameter (ton·year^2/unit^3)
- b_e emissions function parameter (ton·year/unit^2)

c_e emissions function parameter (ton/unit)

P production rate (units/year)

From Zanoni et al. (2014b) we can deduce the average energy used for production activities as:

$$E_M = \left(\frac{W_m}{P_h} + k_m\right) d \tag{H.4}$$

Where:

E_M the amount of energy consumed per cycle (kWh/year)

W_m idle power of the production machine (kW)

k_m energy required by the production machine to produce one unit (kWh/unit)

P_h production rate (units/hour), where 1 year = 300 days x 8 hours/day = 2400 hours

It should be clearly taken note of that one of the underlying assumptions in Richter (1996a) and El Saadany et al. (2013) is that they both assumed instantaneous replenishment of items. However, the GHG emissions and energy used presented in the models of Jaber et al. (2013) and Zanoni et al. (2014a), respectively, are a function of the production rate; that is, they do not assume instantaneous replenishment. As this model is only for illustrative purposes (and for simplicity) the cost functions by Richter (1996a) and El Saadany et al. (2013) shall be used as is and the economic production quantity (EPQ) model will be used to find the production rate required for the GHG emissions and energy used functions. If there is an intention to solve the problem, then the mathematics involved in Richter (1996a) and El Saadany et al. (2013) must be revisited relaxing the assumption of an instantaneous replenishment. In light of the aforementioned discussion, and given the EPQ model, where $x = \sqrt{\frac{2sd}{h\left(1-\frac{d}{P}\right)}}$, it can be rearranged to show that:

$$P = \frac{d}{1-\frac{2sd}{hx^2}} \tag{H.5}$$

$$\text{Where } 1 - \frac{2sd}{hx^2} > 0 \tag{H.6}$$

The ideal objective function is now to minimize EOQ related and non-related costs, the remanufacturing investment cost, the GHG emissions from production, the energy used for production, and the solid waste disposed by the system. The minimization of each of these costs and the environmental factors may not necessarily be feasible, so the objective becomes to jointly minimize an overall objective encompassing all the factors. A number of methods exists that can be used to solve multi-objective optimization problems including aggregating methods, population based non-Pareto methods, and Pareto-based none litist and elitist methods (e.g., Coello, 1999). For illustrative purposes and to keep the model relatively simple, a weighted sum method (an aggregate approach) is considered. Given the nature of the different units of measure involved, each factor must be normalized so that the objective function can be formulated. Under traditional models and decision making supply chains are optimized in order to minimize EOQ-related costs. For this reason, the reference point to which all factors shall be normalized is the optimal policy for the decision variables x, m, n, and ζ that will yield a minimum value of the sum of the EOQ related costs. Based on this policy (x_{ref}, m_{ref}, n_{ref}, and ζ_{ref}), the non-related EOQ costs, the remanufacturing investment cost, the GHG emissions, energy used and solid waste disposed are computed. As a result, there is now a total costs reference, GHG emissions reference, and solid waste reference that can be used for normalization of each factor.

Summarizing, the model is considered in two-fold: first is to minimise regarding EOQ related costs to obtain the reference points for normalisation, and second is to collectively solve for the costs and environmental related factors combined. That is, the first problem is:

$\min\{x, m, n, \zeta\}$ = EOQ related costs ⇒ x_{ref}, m_{ref}, n_{ref}, and ζ_{ref}. Substituting these values into the cost and environmental functions give us the reference values for each factor, and the second problem now is:

$$\min\{x, m, n, \zeta\} = \frac{\text{system total cost}}{\text{reference cost}} w_1 + \frac{\text{GHG emissions}}{\text{reference emissions}} w_2 + \frac{\text{energy used}}{\text{reference energy}} w_3 + \frac{\text{solid waste}}{\text{reference waste}} w_4$$

Where the priority weights are given to the summation of all costs, w_1, the GHG emissions, w_2, the energy for production, w_3, and the solid waste disposed, w_4.

Summing Eqs. (A.8), (A.9), and (A.21) of Appendix A, replacing all β with Eq. (A.21) of Appendix A and substituting with Eq. (H.2) the total system costs, *TSC*, can be written as:

$$TSC = (mr + ns)\frac{d}{x} + \frac{x}{2}\left[h\left(\frac{\left(\frac{(1-\beta)}{1-\beta^{\zeta+1}}\right)^2}{n} + \frac{\left(1-\frac{(1-\beta)}{1-\beta^{\zeta+1}}\right)^2}{m}\right) + u\left(1-\frac{(1-\beta)}{1-\beta^{\zeta+1}}\right) + \frac{u\left(1-\frac{(1-\beta)}{1-\beta^{\zeta+1}}\right)^2(m-1)}{m}\right] + d\left[\frac{(1-\beta)}{1-\beta^{\zeta+1}}(b+e-k)+k\right] + c_{Inv}\left(1-e^{-\theta\zeta}\right) \tag{H.7}$$

Similarly the disposed units may be written as:

$$\text{Solid waste} = \left(\frac{(1-\beta)}{1-\beta^{\zeta+1}}\right)d \tag{H.8}$$

Substituting Eq. (H.5) into Eq. (H.3) the GHG emissions can be written as:

$$\text{GHG emissions} = a_e\left(\frac{d}{1-\frac{2sd}{hx^2}}\right)^2 - b_e\left(\frac{d}{1-\frac{2sd}{hx^2}}\right) + c_e \tag{H.9}$$

Similarly, the energy related costs function is written as:

$$\text{Energy} = \left(\frac{W_m}{\frac{1-\frac{2sd}{hx^2}}{2400}} + k_m \right) d \tag{H.10}$$

Substituting with x_{ref}, m_{ref}, n_{ref}, and ζ_{ref} into Eqs. (H.7), (H.8), (H.9) and (H.10), respectively, and denoting as A, D, B, and C, respectively, we have the reference factors as:

$$\mathrm{A} = (m_{ref}r + n_{ref}s)\frac{d}{x_{ref}} + \frac{x_{ref}}{2}\left[h\left(\frac{\left(\frac{(1-\beta)}{1-\beta^{\zeta_{ref}+1}}\right)^2}{n_{ref}} + \frac{\left(1-\frac{(1-\beta)}{1-\beta^{\zeta_{ref}+1}}\right)^2}{m_{ref}} \right) + u\left(1 - \frac{(1-\beta)}{1-\beta^{\zeta_{ref}+1}}\right) + \frac{u\left(1-\frac{(1-\beta)}{1-\beta^{\zeta_{ref}+1}}\right)^2(m_{ref}-1)}{m_{ref}} \right] + d\left[\frac{(1-\beta)}{1-\beta^{\zeta_{ref}+1}}(b+e-k)+k\right] + c_{Inv}\left(1-e^{-\theta\zeta_{ref}}\right) \tag{H.11}$$

$$B = a_e\left(\frac{d}{1-\frac{2sd}{hx_{ref}^2}}\right)^2 - b_e\left(\frac{d}{1-\frac{2sd}{hx_{ref}^2}}\right) + c_e \tag{H.12}$$

$$C = \left(\frac{W_m}{\frac{1-\frac{2sd}{hx_{ref}^2}}{2400}} + k_m \right) d \tag{H.13}$$

$$D = \left(\frac{(1-\beta)}{1-\beta^{\zeta_{ref}+1}}\right) d \tag{H.14}$$

Accordingly, the suggested model may be written as:

$$\min\{x, m, n, \zeta\} =$$

$$\frac{(mr+ns)\frac{d}{x}+\frac{x}{2}\left[h\left(\frac{\left(\frac{(1-\beta)}{1-\beta^{\zeta+1}}\right)^2}{n}+\frac{\left(1-\frac{(1-\beta)}{1-\beta^{\zeta+1}}\right)^2}{m}\right)+u\left(1-\frac{(1-\beta)}{1-\beta^{\zeta+1}}\right)+\frac{u\left(1-\frac{(1-\beta)}{1-\beta^{\zeta+1}}\right)^2(m-1)}{m}\right]+d\left[\frac{(1-\beta)}{1-\beta^{\zeta+1}}(b+e-k)+k\right]+c_{Inv}\left(1-e^{-\theta\zeta}\right)}{A} w_1 +$$

$$\frac{a_e\left(\frac{d}{1-\frac{2sd}{hx^2}}\right)^2-b_e\left(\frac{d}{1-\frac{2sd}{hx^2}}\right)+c_e}{B}w_2+\frac{\left(\frac{\frac{W_m}{1-\frac{2sd}{hx^2}}+k_m}{2400}\right)d}{C}w_3+\frac{\left(\frac{(1-\beta)}{1-\beta^{\zeta+1}}\right)d}{D}w_4$$

(H.15)

Subject to:

$$x > \sqrt{\frac{2sd}{h}} \quad \text{(H.16)}$$

$\{m, n, \zeta\} \geq 1$, and integer (H.17)

The determination of the priority weights and solving the above problem is beyond the scope of this paper, however, a brief numerical example is provided for illustrative purposes only. This paper does not seek to solve (optimize) this model for all decision variables, but rather illustrate what the model may capture and how it may be used and further developed regarding the modelling of environmentally responsible inventory and reverse logistics models.

According to Richter (1996a), El Saadany et al. (2013), Jaber et al. (2013), and Zanoni et al. (2014b), the following values have been assumed: $d = 1000$, $r = 400$, $s = 1200$, $b = 60$, $k = 40$, $e = 10$, $h = 60$, $u = 30$, $\beta = 0.9$, $a_e = 0.0000003$, $b_e = 0.0012$, $c_e = 1.4$, $W_m = 100$, $k_m = 0.2$, $c_{Inv} = 5000$, and $\theta = 0.3$.

Relevant expertise may be used to determine the values of the priority weights. For this example, priority weights are arbitrarily assumed. For the sake of argument, there is more emphasis given to cost than the other environmental factors, that is: $w_1 = 2$, $w_2 = w_3 = w_4 = 1$, where the summation of all weights is equal to 5. To simplify the optimization process for this illustrative numerical example, the following is also assumed: $n = 3$, $m = 1$, and $\zeta = 2$. The simplified problem now requires a solution for x.

The first step is to obtain the reference values for each factor, which is done by determining a value for x_{ref} that minimizes the EOQ related costs only. Doing so results in a value of $x_{ref} = 419.12$. If this policy is now implemented in the multi-objective model, then a total score of 5 will be realized as each factor will have a value of 1. The second step of the solution process is to apply the model to find a value for x that shall jointly minimize the overall objective based on the priorities set. The result shows a new value of $x = 274.18$ with an overall score of 4.24. Even though the result is jointly minimized, this policy shows an increase in cost by about 2.4% (from $72,413.75 to $74,158.47), but significant reductions in both GHG emissions of 41.1% (from 349.17 tons to 205.65 tons) and energy used for production of 39.4% (from 185,549 kWh to 112,496 kWh), with no change in the amount of solid waste. This result reflects the complexity of the given problem. There may be no solution that can minimize all individual factors simultaneously and trade-offs are inevitable. Table H.1 shows how the different objectives relate to one another and how some of the trade-offs may be present, depending on the focus of the problem. A double arrow represents a significant increase (if pointing up) or decrease (if pointing down). For the one case where the focus is on minimizing GHG emissions, energy may increase or decrease. GHG emissions have a quadratic function with a local minimum where energy reduces exponentially as the production rate is increased. As a result, we have two cases: if the production rate is already high, i.e. beyond the minimum GHG point, then it must be reduced to achieve a minimum level of emissions, which will increase energy usage, whereas, if the production rate was too low, i.e. below the minimum GHG emissions point, then it will be increased to achieve minimum GHG emissions and thus increase energy usage. Table H.1 rather simplifies some of the relationships and further investigation is required for more in depth analysis.

Table H.1 *General relationships between the different objectives*

Managerial Focus	**Costs**	**GHG Emissions**	**Energy**	**Disposal Waste**
MIN Cost	↓↓	↑	↑	↑
MIN GHG emissions	↑	↓↓	↑ **or** ↓	–
MIN Energy	↑	↑	↓↓	–
MIN Disposal Waste	↑	↑	↑	↓↓

Some simple tests showed that for the given production scenario, if the number of times allowed to repair an item exceeds 9 times, then there is no significant reduction in the amount of solid waste generated, that is, there is an increase in cost with no environmental improvement. For a higher investment cost, c_{Inv} (e.g. $100,000 instead of $5,000), it is more economical to recover an item beyond 9 times so as to capture more economic value and environmental performance. This model is by no means a complete model, but rather one for illustrative purposes that shows the potential for the modelling of reverse logistics inventory models with environmental implications. It further shows how a business may benefit from environmental pro-activeness whether through taking advantage of government incentives to be more 'green' or in response to environmental considerations of stakeholders. The illustrative example shows the potential for adding additional environmental factors or other associated costs that may be considered. An example could be to consider the biodegradability of disposed products, chemical or toxic wastes, the contamination of water tables, etc. The normalization of the problem avoids cost estimations that may drive the focus to avoid paying a penalty for exceeding emissions/pollution levels rather than to reduce the environmental impact and increase environmental responsibility and sustainability. This potential comes at a significant complexity in the modelling of reverse logistics inventory models and closed-loop supply chains as the problem will require significant computations and possibly an exact optimal solution may not be reached without exhaustive searches.

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