## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES



Clicours.com

## LIST OF ABBRIEVIATIONS AND ACRONYMS

| | |
|---|---|
| CLSC | Closed-Loop Supply Chain |
| DP | Dynamic Programming |
| EOQ | Economic Order Quantity |
| ERP | Enterprise Resource Planning |
| EU | European Union |
| EU ETS | European Union Emissions Trading Scheme |
| GA | Genetic Algorithm |
| GHG | Greenhouse Gases |
| GSCM | Green Supply Chain Management |
| MDP | Markovian Decision Process |
| MILP | Mixed Integer Linear Problem |
| MOLP | Multi-Objective Linear Programming |
| RGGI | Regional Greenhouse Gas Initiative |
| WCI | Western Climate Initiative |
| WEEE | Waste Electrical and Electronic Equipment |

# INTRODUCTION

## 0.1. Research Context

Originally, supply chains were conceived within a profit maximization or a cost minimization context (Chopra and Meindl, 2015; Rosič and Jammernegg, 2013; Brandenburg et al., 2014; Fahimnia et al., 2015c). After all, business is the creation of economic value (Elkington, 1998). However, these days, a new way of thinking known as sustainable development has emerged.

Sustainability calls for the simultaneous integration of economic, environmental and social objectives which affect supply chain decisions. In this approach, we should not focus only on the capital spent, but also on the environmental and societal equity achieved, as defined by Elkington (1998) in his triple bottom-line approach. Sustainable development spans many new opportunities, but also holds challenges. This demands a wider variety of approaches and a deeper understanding of the sustainability objectives, so that we can improve firms' achievement of them. Besides, sustainable legislation and client awareness add to companies' needs for integrating sustainable development. The challenge is therefore to develop design, planning and control methods to extend the scope of the traditional supply chain to supply chains that are sustainable.

Pioneer companies have already merged this notion into their values (Fiksel, 2010). For instance, the American sportswear brand, Nike, uses recycled polyester and other footwear material in their products. Johnson and Johnson looks to reduce the effect of the carbon footprint of their logistics operations. Besides encouraging their supplier to measure energy consumption and GHG (Greenhouse Gas) emissions, by the end of 2014, they reduced by 9.6% their facilities' $CO_2$ generations. Finally, Toyota and UPS used logistics as a means to reduce their GHG emissions. Carter and Rogers (2008) argue that firms capable of integrating sustainability will outperform firms that do not. In fact, Pagell et al. (2014) and Kim et al. (2014) claim that if current supply chains want to survive, they should change their practices and management models to integrate sustainable goals. While the pressure has grown for companies to do so, evolution of management methods for carrying this out have not seen the same growth.

Sustainable development is defined by the Brundtland Commission (Brundtland et al., 1987) as "the development that meets the needs of the present without compromising the ability of future generation to meet their owns needs." According to Seuring and Müller (2008) this definition necessitates breaking silos and rethinking supply chain methods within a more holistic view. Therefore, once sustainability is added, all decision levels namely strategic, tactical and operational must be extended to integrate sustainability (von Blottnitz and Curran, 2007; Corsano et al., 2011; Sarkis, 2003).

In the stream of strategic supply chain, researchers have already put sustainability on the agenda. Authors Corsano et al. (2011), Chaabane et al. (2012) and Rezaee et al. (2015) have pointed out that when sustainability issues are integrated, the design of supply chains changes. Moreover, they claim that the supply chain network design is critical to meet sustainability objectives. Other strategic subjects that have been extended to cope with sustainable objectives are: product design (Andersson et al., 1998), supplier selection (Bai and Sarkis, 2010; Kumar et al., 2014); supplier co-operation (Hollos et al., 2012); technology selection (Giarola et al., 2012b,a), and transport mode selection (Elhedhli and Merrick, 2012; Hoen et al., 2012).

At the tactical level, Benjaafar et al. (2013); Fahimnia et al. (2015a); Xu et al. (2015) claimed the importance of inventory control and production strategies in meeting sustainability objectives. Inventories are among the main activities of supply chains (Fahimnia et al., 2015c). Some authors have extended the scope of the traditional inventory control to sustainable approaches. In a deterministic context, Hua et al. (2011) and Li and Gu (2012) have proved that production/order quantities are different when sustainability issues are integrated. Moreover, Xu et al. (2015) showed that optimal production levels are highly related to sustainability targets.

Despite the fact that some management systems have evolve to comply with sustainable objectives, Pagell et al. (2014) argues that our present knowledge, especially at the lower decision levels (i.e. tactical and operational) is not enough to create supply chains that are cost efficient and have green performance. Each decision level entail too many variables, too many uncertainties to foresee the effect of sustainability at each level. The challenge is to find new ways in which the three objectives of sustainable development can coexist at the different decision levels. We need to establish new planning methods to aid companies in embracing sustainable goals.

In particular, it has been pointed out that sustainability initiatives and the environmental policies add uncertainties and new assets to manage (such as carbon credits and reverse flows) to the system constraints. While inventory control has proven to help in reducing cost and improving service level by providing flexibility to the systems and a way to react to uncertainty (Hugos, 2012), inventory policies may help to comply with sustainable objectives. This leads to many questions such as: how can the goals of sustainable development can be translated into inventory policies? What new decisions need to be integrated in planning? How can inventory control help achieve sustainable performance? The aim of this work is to enhance the understating of the role of inventory control to comply with sustainable objectives. We need to reformulate previous models to include the three different sustainable objectives. Our primary objective is to help decision-makers to make this transition. Accordingly, in the following section, we define the scope of the problem limited by our research question. Further, we propose a methodology to answer our questions, and finally, we give our thesis outline.

## 0.2. Scope of the problem

Considering that a sustainable supply chain requires a holistic view of the system (Seuring and Müller, 2008), all decisions (i.e. strategic, tactical and operational) need to be restructured throughout supply chains. However, this task cannot be achieved without prior knowledge and learning about the effects of sustainability at the different decision levels.

Under the context of sustainable development, environmental policies receive particular attention. Environmental laws were born to enforce the implementation of sustainable development among firms. It seeks to reinforce the application of sustainable development where development may cause a significant environmental harm to prevent, or, at least, mitigate such harm. In this regards, multiple countries have developed environmental legislation. We can see the

European Union (EU) with the EU emission trading system (EU ETS), and the Directive on waste electrical and electronic equipment (WEEE). The United States has set various legislation regarding the emission of different pollutants as sulfuric acid. California along with several provinces in Canada have integrated a cap-and-trade scheme. In this research, we focus the integration of environmental legislation as a means to incorporate sustainable development into decision-making.

While early research efforts in sustainable schemes were mainly devoted to investigating the impact of environmental policies on the strategic level; at the tactical level, the effect of environmental constraints is not clear nor is understand on the effect sufficient. To the best of our knowledge, there is no study in addressing the impact of environmental legislation on inventory control. The lack of a comprehensive understanding of the influence of environmental regulation on inventory control prevents us from joining various decision levels. A solid grasp of the effects of environmental regulation is required to advance research on the capabilities of inventory control for achieving sustainability objectives.

The aim of this research is to enhance the understanding of the role of inventory control to achieve cost-effective and social and environmentally friendly supply chains. To this end, it is essential to analyze existing inventory management strategies and examine whether or not they are attaining environmental goals. This brings us to our first research question (RQ):

**RQ1:** Are current inventory control policies effective for coping with environmental laws?

In case present inventory policies need to be transformed, we need to gain insight on how inventory policies must be re-structured. To this end, identifying and understanding the interdependencies between environmental and inventory parameters is crucial. Therefore, we can anticipate further strategies for achieving improved environmental performance. Our second research question is formulated as follows:

**RQ2:** What are the key factors in the design of inventory policies to confront environmental constraints?

From the relations established, strengths and weaknesses of inventory control can be identified. This would help us develop an inventory control strategy capable of transforming environmental policies into opportunities and reacting to threatening situations. In this circumstances, joint strategic and tactical planning might have the potential to help tempering risky situations. We state our third research question as follows:

**RQ3:** What opportunities can be found from the use of joint strategic and tactical planning to enhance the environmental performance of a supply chain?

In the following section, we discuss the methodology used to address the research questions mentioned earlier.

## 0.3. Methodology

To answer the questions mentioned above, we investigate the effect of environmental policies in the context of affected sectors. While there are many factors that we do not understand and analytic solutions are scarce, this research uses multiple case studies to investigate and gain insight into the role of inventory control to cope with environmental constraints.

We consider that case studies are a suitable methodology for enabling us to identify and describe critical variables in decision-making on standing case-studies. We use an approach where we will first closely observe details of individual inventory models. Then, we will get a greater perspective by integrating the strategic level. Hence, we will transfer the benefits of inventory control and study how the two decision levels interact. Figure 0.1 provides a description of the proposed methodology. In the following, we describe each step in detail:

### Step 1. Environmental regulation integration into inventory management

This step focuses on answering our first research question: are current inventory policies helpful in meeting environmental targets?

clicours.com

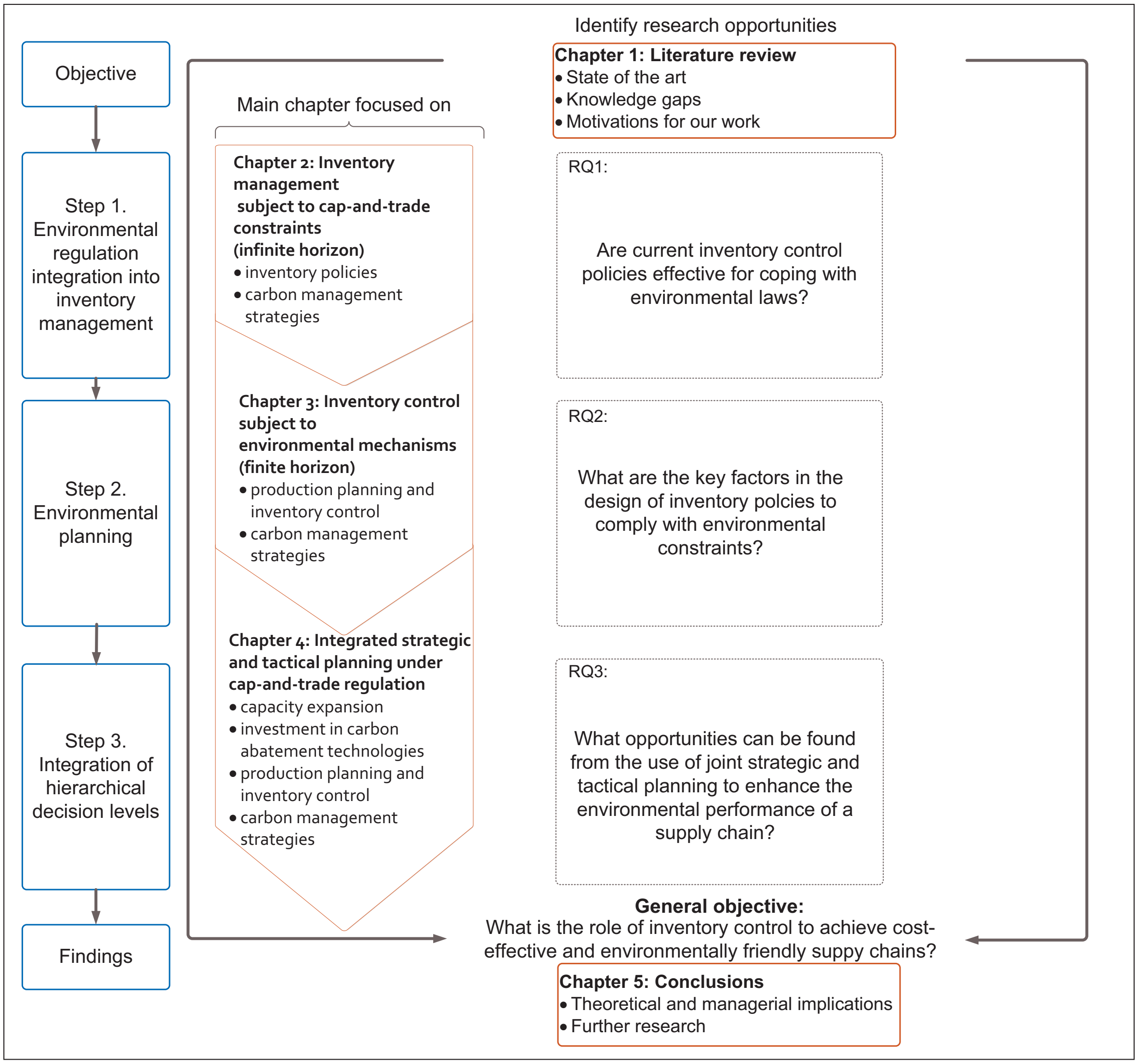


Figure 0.1 Proposed methodology

In this step, we explore ways to integrate environmental legislation into inventory control. To this end, we study several environmental mechanisms and their translation into the objective function and/or constraints. Through case studies, we identify new decisions, states and information required to make inventory policies mesh with environmental goals. We identify the difference between decision-making with and without environmental policies by comparing the structure of inventory policies before and after the inclusion of these. Finally, we emphasize the opportunities for inventory re-design, by measuring the sustainable improvement in terms of economic and environmental performance.

**Step 2. Environmental planning**

The focus of this step is to answer the second research question. What are the key success factors in planning under environmental constraints?

We center on the understanding of the interaction between various environmental parameters and decisions on inventory control. Through numerical studies, we measure the effect and interaction of environmental parameters on economic and environmental performance. From the case studies, we identify key environmental factors and determine the threshold values which affect inventory policies.

**Step 3. Integration of hierarchical decision levels**

Sustainable supply chains require integration and coordination of all decision levels, namely strategic, tactical and operational. The third step addresses the question: What opportunities can be found from the use of joint strategic and tactical planning to improve the environmental performance of a supply chain?

Integration of strategic and tactical decisions is a step forward in building real, sustainable supply chains. Strategic decisions must ensure feasibility of lower decision planning. Indeed, capacity planning is one of the most important topics in this field. To stress the importance of hierarchical integration, we study the simultaneous decision making on capacity planning, investment in carbon abatement technologies, production and inventory control and carbon management. We compare an integrated approach to an isolated tactical planning. Furthermore, we measure the difference in performance regarding profit and environmental achievement. This enables us to highlight the potential benefits and pitfalls of isolated inventory control and the advantages of an integrated approach.

## 0.4. Limitations

There is a gap in the understanding of the implications of sustainability issues at the tactical and operational levels. The aim of this research is to enhance the understanding of the potential of inventory control to improve the sustainable performance of supply chains. Therefore, we bound our research to the tactical and strategic levels.

To be specific, our decisions include, but are not limited to, inventory control, production planning, and carbon management strategies. We integrate into those decisions the economic and environmental performance aspects of sustainability.

One of the key elements of sustainability is the integration of three axes: economic, environmental, and social. However, the difficulties in measuring social performance such as human health, human dignity, and basic needs fulfillment (Hutchins and Sutherland, 2008) have limited the development of performance indicators (Fahimnia et al., 2015a; Brandenburg and Rebs, 2015). The inclusion of environmental policies in decision planning can help to incorporate a sweeping view of the problem. Environmental damage can have consequences on social welfare; hence improvements in environmental effects can also bring about social improvement (Xu et al., 2015). In this work, we considered environmental and social achievement as a single objective.

## 0.5. Thesis outline

The rest of this thesis is organized as follows: In Chapter 1, we survey the literature on sustainable supply chains and highlight knowledge gaps we aim to fill by our research. In Chapter 2, we present an infinite-horizon single-item inventory model for product recovery. We illustrate the integration of environmental policies into inventory control, and highlight the advantages of such integration. We extend inventory management of recovered products under environmental constraints to a finite horizon in Chapter 3. We identify key environmental parameters and study their effect on decision-making. In this section, solution challenges become evident.

Therefore, we propose an alternative approach to extend our results and reduce the computational time.

In Chapter 4, we extend our results to strategic planning. We focus on the potential of the integrated decision levels. We elaborate on the advantages of capacity planning and investments in carbon abatement. We discuss how environmental performance is enhanced in light of sustainable development. Concluding remarks are given at the end of this work, along with a summary of our major findings and a discussion of the future implications of our study.

# CHAPTER 1

# LITERATURE REVIEW

The aim of this chapter is to give a brief review of the key principles of sustainable development applied to supply chains, to provide a state of the art of existing literature in the field of design and planning of sustainable supply chains, and to situate our work.

## 1.1 Fundamentals of sustainable supply chains

Sustainability focus on the three pillars stated by Elkington (1998) namely, financial, environmental and societal. Thus, the concept of sustainable development extends the economic goal of a regular supply chain to ecological and social issues.

A supply chain is defined by Chopra and Meindl (2015) as all functions involved in receiving and filling customer demand. It encompasses manufacturers, suppliers, transporters, warehouses, retailers and customers. Supply chain goal must be to maximize supply chain overall profitability (Chopra and Meindl, 2015), yet conventional supply chains focus primarily on economic and financial business performance (Brandenburg et al., 2014). On the other hand, a sustainable supply chain integrates and coordinates all the aspects of traditional supply chains and also includes the two additional dimensions of sustainable development; namely environmental and societal goals (Seuring and Müller, 2008; Ahi et al., 2013; Brandenburg et al., 2014). Therefore, in this broader perspective of supply chains, environment, and social objectives must be considered as a requirement to fulfill customer needs.

Green supply chain, reverse logistics, and closed-loop supply chain (CLSC) are other frequent topics in the field of sustainable supply chains (Govindan et al., 2015). When only the environmental aspects are integrated into supply chain thinking, it is known as green supply chain management (Srivastava, 2007). Reverse logistics involves the collection, inspection, disassembly, reprocessing, redistribution and reuse of end of life products, and the disposal of associated wastes (Agrawal et al., 2015; Bazan et al., 2016). On the other hand, a closed-loop supply chain integrates and coordinates the forward and reverse supply chain activities (Guide et al., 2003). For an extensive literature on the field, we suggest the works of Fleischmann and Bloemhof-Ruwaard (1997) and Srivastava (2007).

We discuss motivations of sustainable supply chains and performance indicators, among others, in the following sections.

### 1.1.1 Triggers for sustainable supply chains

The adoption of sustainable initiatives is mainly triggered by 1) customers and stakeholders, and 2) legislation (Seuring and Müller, 2008; Walker et al., 2008; Testa and Iraldo, 2010; Hoen et al., 2012).

#### 1.1.1.1 Customers and stakeholders

The objective of supply chains is to fill customer's demand (Chopra and Meindl, 2015). Then, customers are a great motivator for building sustainable supply chains.

Numerous studies reveal the growing pressure exerted by customers for greener products and less polluting processes. For instance, in a study carried out by Letmathe and Balakrishnan (2005), in the United States, more than 60% of customers desist or consider avoiding goods for environmental causes. In a more recent study in China, Zhao et al. (2014) revealed that 71.6% out of 500 interviewed consumers are disposed to pay for high-priced green products. Ultimately, Kassinis and Soteriou (2003) acknowledges the impact of environmental enhancements on profits by growing customer satisfaction on hospitals.

Stakeholders can also influence firms to embrace important goals such as the ones of sustainable development (Schaltegger and Burritt, 2014). The growing number of ecologically conscious customers encouraged stakeholders to pressure organizations to adopt sustainable initiatives. For instance, the study performed by González-Benito and González-Benito (2006) over 186 manufacturing firms reveals that only stakeholder's pressure can justify the implementation of environmental habits in logistics.

#### 1.1.1.2 Environmental policies

Amid growing concerns over climate change, depletion of natural resources and client awareness; a significant number of enactments has emerged all over the world. Laws go from voluntary agreements to complex trading systems, though, they all share the same goal: to encourage companies to curb their emissions or their resource consumption.

We might divide the policies into two categories discussed below: regulatory approaches and market-based approaches. Other mechanisms derive from combinations or special cases of the previous strategies.

**Regulatory approaches: Command and control**

Regulatory approaches also known as command and control, rely on setting a standard environmental performance, defining a particular technology or emission limits without using economic incentives beyond established limits (U.S. Environmental Protection Agency, 2001).

The enforcement of this regulation is made through sanctions. Since the policy tends to restrict compliance options, this strategy is not as flexible as other approaches, but it is effective to carbon mitigation. China was one of the countries to use a command-and-control to climate challenges.

**Market-based approaches**

In contrast to the command and control regulation, market-based policies provide economic incentives to reduce carbon emissions. Two of the most-used approaches are carbon taxes and cap-and-trade mechanisms (Song and Leng, 2012; Hoen et al., 2012; Xu et al., 2015).

Moreover, some authors define these policies as one of the biggest motivators for building green supply chains (Schaltegger and Csutora, 2012).

• A carbon tax is defined as a penalty for greenhouse gas (GHG) emissions, set and controlled by the government (U.S. Environmental Protection Agency, 2001). Under this approach, there is no cap, emitters decide the number of emissions to mitigate based on carbon prices.

Examples of countries that have followed this approach include Australia, Sweden, Norway, South Africa, Mexico and the Canadian province of British Columbia (Schaltegger and Burritt, 2014; Xu et al., 2015).

• An alternative policy to a carbon tax mechanism is a cap-and-trade regulation. In this approach, as in the command and control system, the government set a target on the emission abatement. However, if mandatory levels are not respected multiple options exist.

To meet the environmental targets covered sectors have the possibility to decide whether to modify their processes to reduce their ecological footprint or to buy exceeding emissions in the carbon market. Besides, companies can sell carbon credits if they have an emission surplus. The choice depends on the cost of reducing one metric ton of emissions versus carbon prices. Apparently, the success of the cap-and-trade scheme relies on the force of the market to drive carbon prices.

The main difference with a cap-and-trade policy against the others is that it is possible to buy emissions if caps are exceeded, contrary to the command and control approach. Plus, carbon prices are driven by supply and demand on the market and no by the government as in a carbon tax system. Numerous countries have launched their versions of the cap-and-trade scheme. For instance, countries in the European Union (EU) established the EU emissions trading scheme (EU ETS) in 2005, Tokyo in 2010, U.S. states such as California in 2013 and the Canadian province of Quebec in 2014 (California Air Resources Board, 2014; Xu et al., 2015).

Additional advantages and disadvantages of different environmental policies are listed on the work of Zakeri et al. (2015).

### 1.1.2 Industrial sector background

Although some aspects of the policies and the covered sectors differ by country, for the most part, the policies apply to the most intensive energy and carbon sectors.

For example, the EU ETS and California's cap-and-trade program apply to energy- intensive industries such as oil refineries, iron and steel production, cement, and pulp and paper manufacturing, among others (Hoen et al., 2012; California Air Resources Board, 2014).

### 1.1.3 Measuring sustainability performance

Supply chain models are typically focused on performance indicators such as cost (net profit) and service level (Rosič and Jammernegg, 2013; Chopra and Meindl, 2015). Therefore, extending the scope of supply chains to green and social components evokes addressing the influence and relationships of supply chain activities to the natural environment and social welfare (Hervani et al., 2005).

Because of their significant effects on ecosystems and human health (Schaltegger and Burritt, 2014), authors such as Aronsson and Brodin (2006) and Fahimnia et al. (2015c) have identified GHG emission measurement as one of the most important and recurring methods to evaluate environmental performance. Other authors listed waste generation (Tsai and Hung, 2009), energy use (Cholette and Venkat, 2009) and material consumption (Curran and Brent, 2005) as alternative performance indicators. Meanwhile, well-suited social performance indicators are still missing (Brandenburg and Rebs, 2015). However, some metrics found in literature are: human health (Hutchins and Sutherland, 2008), labor conditions (Mueller et al., 2009) and job-creation (Boukherroub et al., 2015).

In reality, there is no universal way of measuring sustainability (Keating et al., 2008), performance indicators for supply chain must then be formulated in regards to the scope of sustainability focused. Hassini et al. (2012) and Schaltegger and Burritt (2014) present an extended literature review of metrics in the context of sustainable supply chains.

## 1.2 Related literature

According to the scope of this work, we reviewed papers at the strategic and tactical/operational decision levels. At the strategic level, we focused on the work made for building sustainable supply chains and how managerial models have been redesigned to cope with environmental policies. We briefly examine the role of reverse and closed-loop supply chains in this context. At the tactical/operational level, we centered on inventory control and how inventory policies have been adapted to include sustainability initiatives. Ultimately, we identified the main knowledge gaps.

### 1.2.1 Strategic supply chain decisions under environmental policies

In the following, we study the main work made at the strategic level to manage environmental constraints.

#### 1.2.1.1 Network design

Supply chain network design is critical to meet environmental goals (Seuring, 2004; Ramudhin et al., 2010; Chaabane et al., 2011).

Chaabane et al. (2011) are among the pioneers in this field. Their results gave evidence of the advantages of a cap-and-trade mechanism and the benefits of network design to reduce the carbon abatement cost. Giarola et al. (2012a) focused on the design and planning of a multi-echelon supply chain under carbon and biomass cost uncertainty subject to an emission trade scheme. Their findings support that emission trading might represent a cost-effective means to a significant GHG emission mitigation. Elhedhli and Merrick (2012) studied the network design problem taking account emissions from transport. They provided evidence on how the emission cost affects network configuration. Harris et al. (2014) addressed the facility location and allocation problem with a bi-objective approach: costs and $CO_2$ emissions. They showed the trade-off between cost and emission performance. In a more recent research, Rezaee et al. (2015) studied the design and planning of a two-stage network with stochastic demand and carbon prices under carbon trading. They pointed out that supply chain configuration is extremely sensitive to the distribution of carbon prices. In particular, the higher the carbon price is, the greener would be the resulting configuration.

Since reverse logistics and CLSC save the use of virgin material, they are recurring topics in environmental issues (Seuring, 2004; Chouinard et al., 2005; Srivastava, 2007; Dekker et al., 2012). In this context, Chaabane et al. (2012) evaluated the effect of the carbon market on the design of a CLSC. Specifically, they defined the impact of the allowance prices and suggested that legislation at the global level must be established. More recently, Bing et al. (2015) investigated the integration of ecological regulation in the design of a reverse supply chain for household plastic waste recovering. Their results indicate that global relocation of re-processing facilities leads to improvements regarding cost and emissions from transport operations.

#### 1.2.1.2 Investment in carbon abatement technologies

Technology choice and green investments are also important aspects that have been explored by some authors.

One of the pioneers in this field is the work of Hugo and Pistikopoulos (2005). They addressed the selection, allocation and capacity expansion of processing technologies with economic and environmental considerations. They gave proof that substantial improvements in one of the performance criteria (economic and environmental) can be reached by a minimal compromise on the other. Subramanian et al. (2007) modeled a three-stage game and studied pollution-control investments and cap-and-trade schemes. They stated that the number of available permits affects more carbon mitigation levels in a cleaner industry than in a dirty one. Giarola et al. (2012b) addressed the design of a bio-ethanol supply chain and technology choice with financial and environmental considerations. Their results demonstrated the strong impact of environmental objectives on technology decisions and supply chain design.

Krass et al. (2013) contributed to the understanding of the impact of carbon taxes on the choices of carbon abatement technology, production quantities, and price. The authors argue that while emission fees would motivate an initial switch to low-carbon technology, expensive carbon fees would cause the opposite. Drake et al. (2015) later reaffirmed this. Drake et al. (2015) focused on the impact of a cap-and-trade scheme and emission tax on technology choice, capacity decisions, and production quantities. As in Krass et al. (2013), they pointed out that higher emission taxes would encourage lesser environmental investments on cleaner technology. Dong et al. (2014) investigated sustainability investments under a cap-and-trade legislation for centralized and decentralized supply chains. They derived the optimal production/order plan and determined that sustainability investment efficiency has a significant influence on required quantities.

#### 1.2.1.3 Other topics

Transport is a significant contributor to global warming (Fahimnia et al., 2015a). Thus, some authors have narrower their research on this stream. For instance, Hoen et al. (2014) worked on reducing carbon emission by changing transport modes to cope with voluntary carbon emission targets. Their outcomes imply that transport mode selection is a suitable approach for small emission reduction goals. Jin et al. (2014) integrated a cap-and-trade and carbon tax regulation in a supply chain network design and transportation mode selection. They proved that strict emission-caps, and expensive carbon taxes and prices induced the redesign of supply chains. Chen and Wang (2015) studied the transport mode selection problem under numerous emission reduction policies and stochastic demand. They identified transportation mode shifting thresholds under the different laws.

Since now it is hard to distinguish between the sustainable practices of a company and those of the other supply chain's players, cooperation, coordination, and supplier selection are frequent topics in building sustainable supply chains. In the cooperation field, Hollos et al. (2012) studied implications of supplier co-operation according to the axes of sustainable development. The results of their survey to 70 Western European companies expose that sustainable supplier cooperation is beneficial on businesses' performance in the triple bottom line. However, only green actions, not social practices, have significant real impacts on economic performance. In a coordination context, Barari et al. (2012) showed the environmental advantage of coordination between the producer and the retailer. Their outcomes gave proofs that additional greening actions are beneficial because they influence the market. Toptal and Çetinkaya (2015) focused on a buyer-vendor coordination under a cap-and-trade and carbon tax regulation. Their outcomes suggest that although coordination mechanisms aid the buyer and vendor to decrease their costs while complying with environmental policies in some scenarios, this generates an increased carbon footprint. Bai and Sarkis (2010) proposed an approach to integrate sustainability on supplier selection. They provided evidence of the complexity of decision-making facing the economic, environmental and social goals.

### 1.2.2 Tactical and operational decisions under sustainable constraints

While at the strategic level, the inclusion of sustainable development is in its maturity, the advancement at the tactical level is in this infancy. In the following, we explore the work made in this field with a strong emphasis on production planning and inventory control.

#### 1.2.2.1 Sustainable production planning and inventory control

We classified the literature in production planning and inventory control in deterministic and stochastic models.

##### 1.2.2.1.1 Deterministic models

The traditional economic order quantity (EOQ) is one of the most studied models. It considers a known and stationary demand over an infinite horizon. In addition, it aims to determine the optimal lot size while traditionally minimizing the total holding and ordering costs. Many researchers have extended this model to take account of the sustainability issues.

Bonney and Jaber (2011) extended the EOQ model to add the cost of disposal and emissions from transport. Hua et al. (2011) incorporated the cost of the environmental damaged when a cap-and-trade scheme is applied. They pointed out that the lot size is related to the cost, emissions, and legislation. Under the same approach, Wahab et al. (2011) proposed a two-level supply chain model to determine the optimal production – shipment policy with regards to the cost and emission generated from transport. Bouchery et al. (2012) presented the so-called "sustainable order quantity (SOQ)" a multi-objective approach that considered the three pillars of sustainability. In the work of Arslan and Turkay (2013) social and environmental costs were included in the EOQ model. The social issues were translated regarding working hours, and five environmental approaches were studied. Veen and Venugopal (2014) presented a multi-objective approach based on the EOQ model with cost and energy usage considerations. Based on their efficient frontier, the authors provided insight into the trade-off on economic and environmental objectives. Battini et al. (2014) proposed a sustainable EOQ model. The authors integrated the environmental impact of transportation and inventory and investigated their effects concerning cost and carbon footprint. Based on the EOQ model, He et al. (2014) examined the impact of a cap-and-trade mechanism and carbon tax on lot-size. Their findings suggest that the effect of both regulations depends on their parameters.

Recently, other authors have continued to extend the scope of the EOQ model to minimize in parallel emissions and factors such as fuel and energy. For instance, Gurtu et al. (2015) focused on the impact of fuel price and emissions on the EOQ model. They gave proof of how the order cost and lot size change when fuel prices and emission taxes are permuted. Bazan et al. (2015a) explored a reverse logistics mathematical model based on the EOQ setting along with the cost of GHG emissions and energy usage. They focused on determined the optimal size batch for manufacturing and remanufacturing along with the number of times to remanufacture a product. Their findings on the remanufacuturing of tires support that when the number of recovered items is low, it would be better to reduce the number of times a tire is remanufactured to minimize the carbon footprint of the company. Bozorgi (2016) presented a variation of the EOQ model. They examined a multi-objective (cost and emissions) inventory model for cold items. The proposed model outperforms, respectively, the EOQ model and the SOQ model developed by Bouchery et al. (2012).

The Arrow-Karlin model has also been extended to cope with environmental issues. In this model, it is assumed pollution as a non-decreasing and convex function of the production rate. In this context, Wirl (1991) proven than emission taxes would encourage higher inventory levels and lower production rates. Xepapadeas (1992) investigated the effect of emission caps and production and inventory levels. Dobos (1999) introduced emission limits and taxes into their production-inventory strategy. Their findings show that legislation would be ineffective if established limits are greater than the optimal production levels in a cost minimization context. Later, their work was extended to an emission trading scheme by Dobos (2005). Their outcomes attest that production and inventory optimal levels will not be the same with or without emission trading. Moreover, the effects of the environmental policy would coincide with those of Wirl (1991) and Dobos (1999). A final extension was made by Dobos (2007) to study the influence of carbon prices on production and inventory levels. They proved that the total cost will be increased and the production-inventory strategy will change after introducing emission trading. In fact, in comparison to an scenario without trading, inventory levels would be higher and production rate would decrease. The work of Dobos (2007) was extended by Li and Gu (2012). They focused on emission banking, and observed the same behavior that Dobos (2007) on production and inventory.

Under a deterministic context, Letmathe and Balakrishnan (2005) presented two models to help companies determine their optimal production planning under environmental regulation. Benjaafar et al. (2013) studied multiple lot-sizing models to show the effect of carbon regulation on procurement, production and inventory management. They argue that carbon abatement objectives can be attained only by operational modifications. Absi et al. (2013) also explored a lot-sizing problem under several carbon constraints. They gave insights on the structure of the model and developed on solution methods. Similar to Absi et al. (2013), Helmrich et al. (2015) investigated a lot-sizing problem but with a constraint on the total amount of emissions generated. The authors gave insight into the structural properties of the model. Fahimnia et al. (2013) investigated the effect of carbon tax on the tactical-operational planning of a forward supply chain and a CLSC. According to their results, expanding the scope of a forward supply chain to include reverse activities may be disadvantageous to a firms' carbon footprint, but other ecological benefits should not be unnoticed. Later, Fahimnia et al. (2015a,b) studied the effect of carbon tax on a supply chain planning problem with economic and environmental considerations. Zakeri et al. (2015) compared a carbon tax against a carbon trading scheme on a supply chain planning problem. The authors claim that a cap-and-trade scheme out-performed the carbon tax approach in terms of emission, costs and service level. Although, a carbon tax may be a better approach when the uncertainty of the market is considered. Xu et al. (2015) also compared the effect of both regulations on the carbon footprint, profits, and social welfare. They focused on the joint production and pricing problem of a manufacturing firm with multiple products. They found that optimal production levels depend on the carbon price.

#### 1.2.2.1.2 Stochastic models

Most of real-life systems have uncertain particularities; therefore, some stochastic models have also been extended to sustainability objectives.

In a non-stationary, single-period model, the newsvendor model is one of the most extended models. Manikas and Godfrey (2010) proposed a newsvendor model to estimate optimal production quantities in the presence of emission permits and penalties. They proved that the number of permits, permit fees, and penalty fees are inversely related to the quantity to manufacture. Song and Leng (2012) focused on the effect of the emission-caps, carbon taxes, and emission-trading. For the emission-cap, their results are similar to those of Dobos (1999), to be an effective policy the limit must trigger a minor quantity. Meanwhile, under a cap-and-trade policy, the emission cap must be such as the marginal profit is lower than the carbon price. Otherwise, the emission-cap would be not respected.

Based on the newsvendor framework, Rosič and Jammernegg (2013) analyzed companies' decisions on a dual sourcing model considering emission from transport from one of the sources. They pointed out that given the flexibility of the cap-and-trade scheme; it is a preferred mechanism. Zhang and Xu (2013) with an approach multi-item, derived the optimal order quantity for retailers subjected to the cap-and-trade mechanism. Their study shows that low-emission products would be preferred over high-emissions items when a cap-and-trade system exists. Using newsvendor hypothesis, Hoen et al. (2012) focused on determining simultaneously transport mode selection, and inventory policies to reduce carbon emissions. They found that mode selection decisions can obtain different emission reductions, but decisions highly depend on the regulation and non-monetary considerations, such as lead time variability.

Following another approach, Gong and Zhou (2013) studied a single-production, multi-period, production planning problem with emission trading. They gave insights into the characterization of the optimal production and trading policies. The authors emphasize that policies depend on more states and are not as simple in the traditional. In a more recent study, Purohit et al. (2015) focused on a lot-sizing problem under stochastic demand and a cap-and-trade mechanism. The authors argue that demand uncertainty increases not only costs but emissions as well. In the context of reverse logistics, Ahiska and King (2010) focused on production planning with recovery and set-ups. The authors characterized the structure of the optimal policy.

#### 1.2.2.2 Other topics

Other studies that must be stressed at the tactical level is the work of Zanoni et al. (2014) and Bazan et al. (2015b). Zanoni et al. (2014) studied the joint economic lot sizing problem (JELSP) subject to environmental legislation and consignment stock. The authors gave proof that decisions are sensitive to emissions. Later on, their work was extended by Bazan et al. (2015b) to include energy usage. They authors claim that prioritizing GHG reductions may come in conflict with economic goals.

Bauer et al. (2009) integrated GHG emission cost into freight transportation planning and provided a multi-commodity capacitated network design to minimize the environmental impact of transport. Under the same context, Kim et al. (2009) studied the trade-offs between freight transport cost and carbon emissions. Capacities of systems are pointed out to be a factor of great significance in decisions.

Validi et al. (2013) studied a low-carbon distribution network. They extended the traditional approach to incorporate the rate of carbon emissions and fuel consumption. Later, Validi et al. (2014) studied a capacitated distribution system for the dairy industry. They focused on the minimization of carbon emissions from transport and total costs.

## 1.3 Research gaps and discussion

Tables 1.1 to 1.6 summarize the literature review. We are interested in pointing out the planning problems that have been jointly studied in the context of sustainable supply chains. More specifically, we highlighted whether the literature considers profit maximization or cost minimization, carbon footprint reduction or inclusion of environmental legislation such as carbon tax, direct-cap or cap-and-trade, deterministic or stochastic scenarios, and other unique issues.

We list the knowledge gaps found in the literature as follows:

a. There is a variety of research in the field of decision-making at the strategic level, yet sustainability necessitates a holistic view. The effect of sustainable objectives at the tactical/operational level is not clear.

b. Inventory control has been identified in the literature as a core activity in the supply chain; nevertheless, its role in improving the sustainability performance of firms is not well-understood.

c. The approaches adopted in literature for integrating environmental legislation into inventory control are, for the most part, limited to minimization cost and deterministic scenarios.

d. There is no comprehensive study of the dynamics of environmental legislation. Besides, the critical parameters of environmental regulation and their effects on inventory control are not clear.

The new environmental constraints pose unknown challenges to previous management approaches. The literature has been focusing on strategic decisions such as network design and facility location to cope with environmental policies. Because of the intrinsic characteristics of tactical/operational decision models, very few authors have tackled the redesign of inventory policies. Incorporating environmental laws into inventory decisions will help to support strategic goals, and it may help companies to increase their environmental performance.

So far, inventory models that consider environmental constraints are frequently based on the EOQ model. Moreover, most of the models aim to minimize cost using single period and deterministic assumptions. Deterministic models may be easier to solve than stochastic models; nevertheless, inventory problems joint to environmental aspects are confronted with several uncertainties such as random demand, returns, carbon price and availability uncertainty. Therefore, typical assumptions such as a deterministic environment may not capture all the complexity of the real-world problems.

The majority of works integrating environmental legislation relax their dynamics. For instance, most of the models take the environmental law into consideration by setting emission limits or taxes. However, an environmental mechanism such a cap-and-trade scheme which involves purchase and sale of carbon credits necessitates more detailed models that consider quantity and period to buy/sell carbon credits. A proper understanding of the impact of environmental policies on inventory decisions may be critical for reducing environmental impact and improving profits.

### 1.4 Conclusions

In the last years, companies have been confronted with the integration of sustainable objectives. Clients and environmental legislation are putting pressure on firms to minimize GHG emissions through all their supply chains. In this regards, very few research has been made to integrate environmental goals into inventory control, considered as a core activity in the supply chain.

In this chapter, we reviewed papers related to inventory control subject to environmental constraints. Although the number of papers in the field is increasing, the current literature is insufficient to have a clear understanding of the potential of inventory control to improve environmental performance. In general, multiple particularities of inventory control and environmental constraints have been relaxed on the existing models. Most of them are based on EOQ model where scenarios are considered deterministic and single-period, that may relax the complexities of the real world. To provide further insights, researchers and practitioners need to take a deeper view of the integration of environmental policies into inventory control. Models should integrate innate uncertainties of inventory control and environmental legislation such as random demand and carbon prices.

To enhance the understanding of the role of inventory control in coping with environmental constraint, our study also highlights the need for a more comprehensive evaluation of the impact of GHG emission reduction policies on inventory models. So far, the majority of the work reviewed in general simplifies the features of the environmental legislation. More detailed models that capture the dynamics of environmental mechanisms are required. Besides, the joint study of carbon management and inventory policies have also been neglected.

Better suited inventory models may improve environmental performance and reduce costs, which are the main challenges faced by decision-makers in supply chains. Our research fills the gap in the literature by 1) exploring the inclusion of environmental mechanisms in inventory control; 2) analyzing the effect of environmental legislation and its parameters on inventory management, and 3) defining the potential of inventory control to comply with sustainable goals, which might have the potential to help further improve the sustainable efficiency of supply chains.

Table 1.1 Summary of planning problems covered by the reviewed works

| Study | Planning problems | | | | |
|---|---|---|---|---|---|
| | Capacity expansion | Investments | Inventory control | Production planning | Carbon management |
| Wirl (1991) | | | • | • | |
| Xepapadeas (1992) | | | • | • | |
| Dobos (1999) | | | • | • | |
| Hugo and Pistikopoulos (2005) | • | | | • | |
| Dobos (2005, 2007) | | | • | • | |
| Letmathe and Balakrishnan (2005) | | | | • | |
| Subramanian et al. (2007) | | • | | | • |
| Manikas and Godfrey (2010) | | | | • | |
| Bonney and Jaber (2011) | | | • | | |
| Chaabane et al. (2011) | | | | • | |
| Hua et al. (2011) | | | • | | |
| Wahab et al. (2011) | | | • | | |
| Bouchery et al. (2012) | | | • | | |
| Chaabane et al. (2012) | | | | • | • |
| Elhedhli and Merrick (2012) | | | | • | |
| Giarola et al. (2012a) | • | • | | | |
| Giarola et al. (2012b) | • | • | | | |
| Hoen et al. (2012) | | | • | • | |
| Li and Gu (2012) | | | • | • | |
| Song and Leng (2012) | | | | • | |
| Absi et al. (2013) | | | | • | |
| Arslan and Turkay (2013) | | | • | | |
| Benjaafar et al. (2013) | | | | • | |
| Fahimnia et al. (2013) | | | | • | |

Table 1.2 Summary of planning problems covered by the reviewed works (continued)

| Study | Planning problems | | | | |
|---|---|---|---|---|---|
| | Capacity expansion | Investments | Inventory control | Production planning | Carbon management |
| Gong and Zhou (2013) | | | | • | • |
| Krass et al. (2013) | | • | | • | |
| Zhang and Xu (2013) | | | | • | |
| Harris et al. (2014) | | | | | |
| Hoen et al. (2014) | | | | • | |
| Drake et al. (2015) | • | • | | • | |
| Dong et al. (2014) | | • | | • | |
| Veen and Venugopal (2014) | | | • | | |
| Battini et al. (2014) | | | • | | |
| He et al. (2014) | | | • | | |
| Fahimnia et al. (2015a) | | | | • | |
| Fahimnia et al. (2015b) | | | | • | |
| Zanoni et al. (2014) | | | | • | |
| Bazan et al. (2015a) | | | • | | |
| Bazan et al. (2015b) | | | | • | |
| Bing et al. (2015) | | | | • | |
| Gurtu et al. (2015) | | | • | | |
| Helmrich et al. (2015) | | | | • | |
| Purohit et al. (2015) | | | • | • | |
| Rezaee et al. (2015) | | | | • | • |
| Xu et al. (2015) | | | | • | |
| Zakeri et al. (2015) | | | | • | |
| Bozorgi (2016) | | | • | | |

Table 1.3 Summary of economic and environmental issues covered by the reviewed works

| Study | Economic considerations | | Environmental considerations | |
|---|---|---|---|---|
| | Minimizing cost | Maximizing profit | Carbon footprint reduction | Environmental regulation |
| Wirl (1991) | ● | | ● | ● |
| Xepapadeas (1992) | ● | | ● | ● |
| Dobos (1999) | | ● | ● | ● |
| Hugo and Pistikopoulos (2005) | | ● | ● | |
| Dobos (2005, 2007) | ● | | ● | ● |
| Letmathe and Balakrishnan (2005) | ● | | ● | ● |
| Subramanian et al. (2007) | | ● | ● | ● |
| Manikas and Godfrey (2010) | | ● | ● | ● |
| Bonney and Jaber (2011) | ● | | ● | |
| Chaabane et al. (2011) | ● | | ● | ● |
| Hua et al. (2011) | ● | | ● | ● |
| Wahab et al. (2011) | ● | | ● | |
| Bouchery et al. (2012) | ● | | ● | |
| Chaabane et al. (2012) | ● | | ● | ● |
| Elhedhli and Merrick (2012) | ● | | ● | |
| Giarola et al. (2012a) | | ● | ● | ● |
| Giarola et al. (2012b) | | ● | ● | |
| Hoen et al. (2012) | ● | | ● | ● |
| Li and Gu (2012) | ● | | ● | ● |
| Song and Leng (2012) | | ● | ● | ● |
| Absi et al. (2013) | ● | | ● | ● |
| Arslan and Turkay (2013) | ● | | ● | ● |
| Benjaafar et al. (2013) | ● | | ● | ● |
| Fahimnia et al. (2013) | ● | | ● | |

Table 1.4 Summary of economic and environmental issues covered by the reviewed works (continued)

| Study | Economic considerations | | Environmental considerations | |
|---|---|---|---|---|
| | Minimizing cost | Maximizing profit | Carbon footprint reduction | Environmental regulation |
| Gong and Zhou (2013) | • | | • | • |
| Krass et al. (2013) | | • | • | • |
| Zhang and Xu (2013) | | • | • | • |
| Harris et al. (2014) | • | | • | |
| Hoen et al. (2014) | | • | • | • |
| Drake et al. (2015) | | • | • | • |
| Dong et al. (2014) | | • | • | • |
| Veen and Venugopal (2014) | • | | • | |
| Battini et al. (2014) | • | | • | |
| He et al. (2014) | • | | • | • |
| Fahimnia et al. (2015a) | • | | • | |
| Fahimnia et al. (2015b) | • | | • | |
| Zanoni et al. (2014) | • | | • | • |
| Bazan et al. (2015a) | • | | • | • |
| Bazan et al. (2015b) | • | | • | • |
| Bing et al. (2015) | • | | • | • |
| Gurtu et al. (2015) | • | | • | • |
| Helmrich et al. (2015) | • | | • | • |
| Purohit et al. (2015) | • | | • | • |
| Rezaee et al. (2015) | • | | • | • |
| Xu et al. (2015) | | • | • | • |
| Zakeri et al. (2015) | • | | • | • |
| Bozorgi (2016) | • | | • | |

Table 1.5 Summary of special issues integrated into supply chains

| Study | Uncertainty | | Other characteristics | | |
|---|---|---|---|---|---|
| | Demand | Returns | Forward network | Reverse network | Multi-period |
| Wirl (1991) | | | • | | |
| Xepapadeas (1992) | | | • | | |
| Dobos (1999) | | | • | | |
| Hugo and Pistikopoulos (2005) | | | • | | • |
| Dobos (2005, 2007) | | | • | | |
| Letmathe and Balakrishnan (2005) | | | • | | |
| Subramanian et al. (2007) | | | • | | |
| Manikas and Godfrey (2010) | • | | • | | |
| Bonney and Jaber (2011) | | | • | | |
| Chaabane et al. (2011) | | | • | | |
| Hua et al. (2011) | | | • | | |
| Wahab et al. (2011) | | | • | | |
| Bouchery et al. (2012) | | | • | | |
| Chaabane et al. (2012) | | | • | • | |
| Elhedhli and Merrick (2012) | | | | • | |
| Giarola et al. (2012a) | | | • | | • |
| Giarola et al. (2012b) | | | • | | • |
| Hoen et al. (2012) | • | | • | | • |
| Li and Gu (2012) | | | • | | |
| Song and Leng (2012) | • | | • | | |
| Absi et al. (2013) | | | • | | • |
| Arslan and Turkay (2013) | | | • | | |
| Benjaafar et al. (2013) | | | • | | |
| Fahimnia et al. (2013) | | | • | • | • |

Table 1.6 Summary of special issues integrated into supply chains (continued)

| Study | Uncertainty | | Other characteristics | | |
|---|---|---|---|---|---|
| | Demand | Returns | Forward network | Reverse network | Multi-period |
| Gong and Zhou (2013) | • | | • | | • |
| Krass et al. (2013) | | | • | | |
| Zhang and Xu (2013) | • | | • | | |
| Harris et al. (2014) | | | • | | |
| Hoen et al. (2014) | | | • | | |
| Drake et al. (2015) | • | | • | | |
| Dong et al. (2014) | • | | • | | |
| Veen and Venugopal (2014) | | | • | | |
| Battini et al. (2014) | | | • | | |
| He et al. (2014) | | | • | | |
| Fahimnia et al. (2015a) | | | • | | • |
| Fahimnia et al. (2015b) | | | • | | • |
| Zanoni et al. (2014) | | | • | | |
| Bazan et al. (2015a) | | | • | • | |
| Bazan et al. (2015b) | | | • | | |
| Bing et al. (2015) | | | | • | |
| Gurtu et al. (2015) | | | • | | |
| Helmrich et al. (2015) | | | • | | |
| Purohit et al. (2015) | • | | • | | • |
| Rezaee et al. (2015) | • | | | | |
| Xu et al. (2015) | | | • | | |
| Zakeri et al. (2015) | | | • | | • |
| Bozorgi (2016) | | | • | | |

## CHAPTER 2

## INVENTORY MANAGEMENT UNDER JOINT PRODUCT RECOVERY AND CAP-AND-TRADE CONSTRAINTS

Marthy García Alvarado[1], Marc Paquet[1], Amin Chaabane[1], Lionel Amodeo[2]

[1] Department of automated manufacturing engineering, École de technologie supérieure,

1100 Notre-Dame Ouest, Montreal, Quebec, Canada H3C 1K3

[2] LOSI, Université de Technologie de Troyes,

BP 2060, 10010 Troyes Cedex, France

Paper submitted to Journal of Cleaner Production in September 2015.

### Abstract

The influence of environmental legislation in inventory control policies is explored. Previous work on product recovery is extended using the introduction of a cap-and-trade mechanism in an infinite-horizon inventory system in which demand and returns are uncertain. Demand is met through two different sources namely manufacturing and remanufacturing, which differ in cost and greenhouse gas emissions. The main contributions of this paper are 1) comparison of system operation in terms of cost and environmental performance under conventional and green inventory policies, and 2) managerial insights into the structure of green inventory policies. To illustrate the impact of a cap-and-trade scheme, a numerical example is used. We solved the problem as a Markovian decision process, and characterized the inventory policies based on the optimal replenishment strategy. We also conducted a sensitivity analysis to examine the effect of underlying environmental parameters as the emission cap and the allowance price in the policy structures. The results indicate that decisions are sensitive to carbon prices. The inventory policy could play an important role in compliance with environmental legislation, although there is threshold carbon price beyond which the company must focus on strategic decisions rather than tactical decisions.

**Keywords:** inventory control, green supply chain management, remanufacturing, cap-and-trade, markov decision processes

## 2.1 Introduction

Several factors, including natural resource depletion and growing environmental concerns and legislation, have forced businesses to redesign their supply chain in order to achieve sustainable objectives, namely economic, environmental and societal goals. For instance, companies operating in the pulp and paper, iron and steel industries have to reuse recovered materials more intensively in their process and also to reduce greenhouse gas (GHG) emissions (Benjaafar et al., 2013). In this specific context, product recovery and GHG reduction strategies are jointly used by supply chain managers to minimize the environmental impact of logistics and supply chain activities.

Motivations for recovery include the reduction of costs associated with raw materials and waste disposal, and in many cases with compliance with law. Moreover, using recovered materials might help to reduce GHG emissions. For example, recycled plastic can be used in industrial manufacturing to partly replace virgin plastics and reduce waste. The study of Wong (2010) also confirms that the recycling of recovered plastics has less environmental impact than the use of crude oil to produce virgin plastics. Recycled plastic saves more than 40% of the carbon emissions of processing new polymer (Wong, 2010).

Triggers for GHG reduction are mainly new environmental laws and regulations such as the Western Climate Initiative (WCI) launched in 2010 (Seuring and Müller, 2008). The aim of the WCI is to reduce the 2005 level of GHG emissions by 15% by the year 2020. This program is based on a cap-and-trade scheme. Under this policy, the total quantity of emissions generated by regulated industries within a given period must be below an emission cap. Several Canadian provinces, as well as some U.S. states, have already signed on to the WCI program.

Early research efforts in product recovery and a cap-and-trade scheme (Chaabane et al. (2012); Palak et al. (2014); Devika et al. (2014)) were largely devoted to understanding the impact of environmental policies at the strategic level. The authors concluded that strategic decisions are tied to environmental policies. Likewise, the importance of tactical and operational decisions in emission reduction is empathized by the studies of Benjaafar et al. (2013), Fahimnia et al. (2015a), Fahimnia et al. (2015b), Bing et al. (2015), Pan and Li (2015), and Ben-Salem et al. (2015). Nevertheless, the role that could play inventory policies in the presence of environmental legislations is still not clear and more studies are necessary.

This paper focuses primarily on inventory control in supply chains where joint product recovery and GHG reduction mechanisms are used to improve the environmental performance with minimum cost increase. Inventory control plays a major role in supporting financial objectives. However, to the best of our knowledge, studies on whether inventory control could play an important role to improve the environmental performance of a company do not explicitly exist. As a result, this study seeks to examine how inventory control policies with remanufacturing should be adjusted in the presence of a cap-and-trade scheme. Thus, the objective of this work is threefold: to develop a stochastic environmental model of inventory control with remanufacturing subject to a cap-and-trade scheme; to characterize the structure of the inventory policies and to determine the impact of the emission cap and the allowance price; to compare the economic and environmental impact of applying the new policies into inventory control.

The rest of the paper is organized as follows. In Section 2.2, we present a literature review on product/material recovery and environmental inventory models. The mathematical formulation of the problem is presented in section 2.3. Using a numerical example, we illustrate the details of the proposed inventory model and the effect of varying the parameter values in Section 2.5. We discuss the results of the numerical analysis in Section 2.6. Our conclusion and proposals for further work are presented in Section 2.7.

## 2.2 Literature Review

Our research is focused on two subjects, namely periodic review recovery inventory control, and environmental inventory control.

The first study of a periodic-review approach with random demand and returns was presented by Simpson (1978). Using dynamic programming, the author characterized the optimal periodic policy in cases involving product recovery. This policy is defined in terms of three parameters per period ($S_p$,$S_r$,$U$), which respectively denote the impetus to produce, remanufacture and dispose. Inderfurth (1997) extended the above model to include lead-time. Van der Laan et al. (2004) extended the Inderfurth (1997) model, introducing a hybrid system under finite horizon with different lead-times, demand and returns. Ahiska and King (2010) similarly extended the van der Laan et al. (2004) model by considering non-zero manufacturing and remanufacturing setup costs and different lead-time structures. By modeling the system as a discrete-time Markovian decision process (MDP), they characterized the optimal policy. Finally, Alinovi et al. (2012) evaluate the effectiveness of return policies in a stochastic inventory model for hybrid systems. They concluded that uncertainty affects the return policy and stochastic product returns made recovery less appealing.

The second stream of research involves environmental policies on supply chain decisions. In view of our stated research problem, we focus on the cap-and-trade mechanism that works as follows. At the beginning of a compliance period, regulated industries are granted with an amount of emissions known as an "emission cap."During allowance auctions companies may purchase or sell allowances in the carbon market. At the end of the compliance period, companies must be below the emission cap to meet the legal requirements. The emission cap, compliance periods and covered sectors are defined by legislators (California Air Resources Board, 2014). In contrast, the allowance price is mainly defined by the carbon market, although legislation also establishes some rules. Figure 2.1 illustrates the dynamics of a cap-and-trade strategy. For an extended literature review on environmental strategies, we refer the reader to the work of Benjaafar et al. (2013).

Previous studies that incorporate environmental constraints at the strategic level include the work of Chaabane et al. (2012). The authors addressed the inclusion of the carbon market into the design of a supply chain using a multi-objective linear program. Formulating their system using mixed integer programming, Palak et al. (2014) studied the impact of environmental legislation on the selection of suppliers and transportation mode in a biofuel supply chain. Devika et al. (2014) presented and compared multiple-solution approaches to a multi-objective closed-loop network problem integrating the three pillars of sustainable development. Finally, Bing et al. (2015) studied the design of a reverse supply chain subject to emission trading schemes. Focused on the household plastic waste scenario, the authors gave insights on the impact of GHG reduction strategies on deciding relocation of re-processing centers.

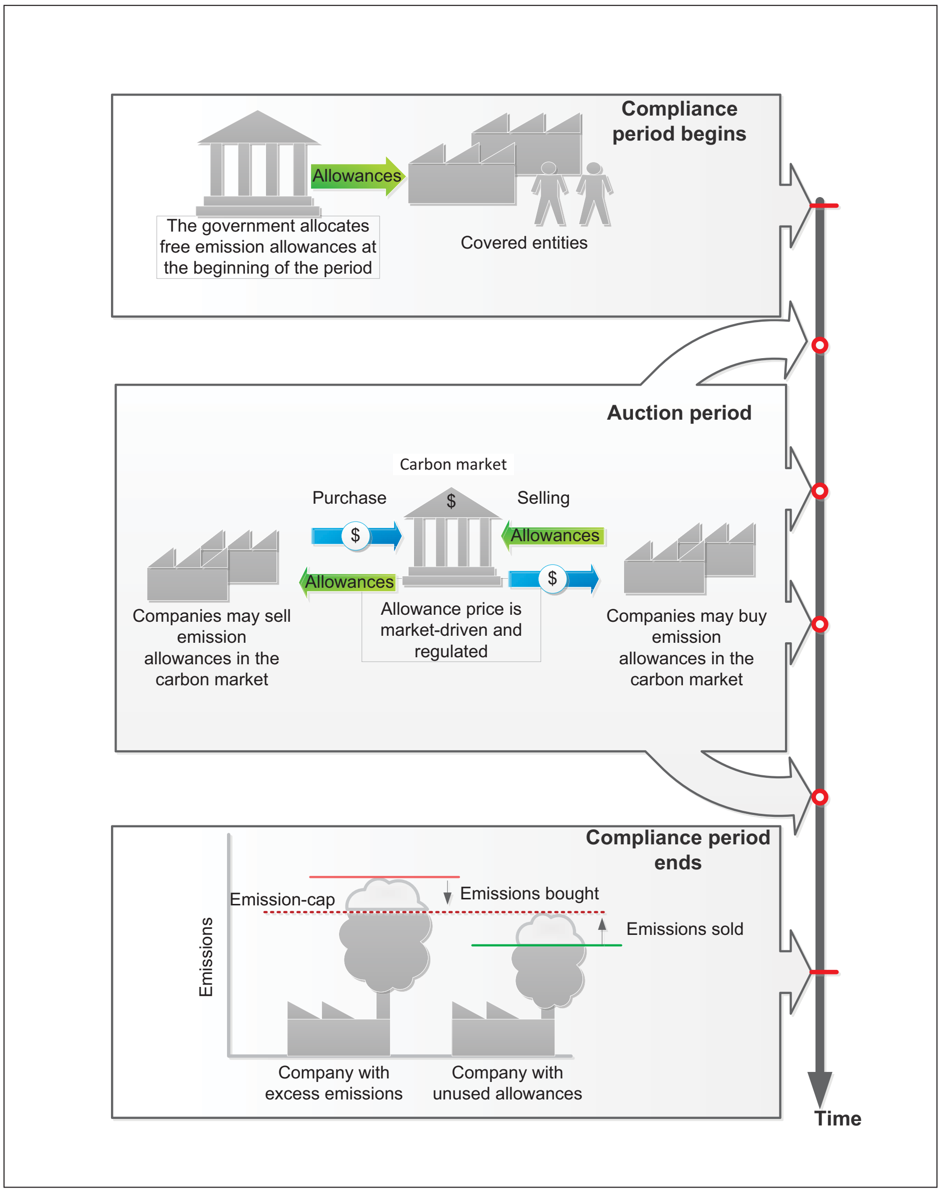


Figure 2.1 A cap-and-trade scheme

Among published studies with a tactical orientation, Bonney and Jaber (2011) propose an extension of the economic order quantity (EOQ) model called “Enviro-EOQ,”in which the costs of disposal and transport-associated emissions are considered. The authors concluded that when environmental costs are introduced, the size of the lot is larger than indicated by the traditional EOQ model. Hua et al. (2011) extended the EOQ model to include the cost of environmental damage. They determined the effect of economic lot size, carbon price, emissions and legislation on the total cost. Yet another EOQ study is that of Bouchery et al. (2012), they presented a form of EOQ called the “sustainable order quantity,”a multi-objective model coupled with an iterative approach that allows interaction with decision makers. Chen et al. (2013), studied the minimization of the total cost subject to an emission cap, proved that a cap is effective only when it is low enough to trigger a change in the quantities ordered. Benjaafar et al. (2013) provided managerial insights emphasizing the importance of operational decisions in emission reduction. Using a set of models the authors showed how adjustments in procurement, production and inventory decisions can reduce carbon emissions. Fahimnia et al. (2013) studied a closed-loop supply chain subject to a carbon tax. The authors defined how carbon pricing influences production and distribution allocation strategies. Later on, Fahimnia et al. (2015a) studied a supply chain optimization problem with parallel objectives: economic and carbon emission reduction. The authors focused on the effect of carbon pricing on manufacturing and distribution planning decisions. Later on, Fahimnia et al. (2015b) presented a tactical supply chain planning model subject to a carbon tax policy. Through numerical examples, they characterized the behavior of the system given different carbon taxes.

A stochastic scenario of inventory greening is the subject of a study by Song and Leng (2012). The authors explored the newsvendor problem subjected to several environmental constraints, providing the optimal production quantity and expected profit in each case. Using the same approach, Hoen et al. (2012) focused in transport mode selection, in an attempt to reduce carbon emissions. Lately, García-Alvarado et al. (2014) extended the work of Ahiska and King (2010). They explored a hybrid inventory model with stochastic demand and returns subjected to a cap-and-trade scheme. In their study, they characterized the structure of inventory policies facing environmental constraints, and provided a simple study of the implications of environmental policies on inventory policy with remanufacturing. Using optimal control theory, Pan and Li (2015) studied a stochastic production-inventory problem with deteriorating items and pollution abatement strategies subject to an emission tax. Using the same approach Ben-Salem et al. (2015) proposed the "Environmental Hedging Point Policy,"a hedging point policy integrating environmental issues into unreliable manufacturing systems.

Table 2.1 summarizes the reviewed papers and positions our work. In spite of interest in recovery systems and integration of environmental constraints into inventory control, only the work of García-Alvarado et al. (2014) appears to have considered combining these fields. In view of this gap in the literature, in this paper we extend the experimental evaluation and the managerial analysis of García-Alvarado et al. (2014). Our main objectives are thus to compare inventory control with remanufacturing without environmental constraints to systems operating under environmental legislation, and to gain managerial insight into the impact of environmental legislation on inventory control policies.

Table 2.1 Literature Review

| Studies | Production planning | Inventory Control | Reverse logistics | Environmental policies | Stochastic Demand | Stochastic Returns |
|---|---|---|---|---|---|---|
| (Simpson, 1978) | | X | X | | X | X |
| (Inderfurth, 1997) | | X | X | | X | X |
| (van der Laan et al., 2004) | | X | X | | X | X |
| (Ahiska and King, 2010) | | X | X | | X | X |
| (Bonney and Jaber, 2011) | | X | | X | | |
| (Hua et al., 2011) | | X | | X | | |
| (Alinovi et al., 2012) | | X | X | | X | X |
| (Chaabane et al., 2012) | | | X | X | | |
| (Bouchery et al., 2012) | | X | | X | | |
| (Song and Leng, 2012) | X | | | X | X | |
| (Hoen et al., 2012) | | | | X | X | |
| (Chen et al., 2013) | X | | | X | | |
| (Benjaafar et al., 2013) | X | X | | X | | |
| (Fahimnia et al., 2013) | X | | X | X | | |
| (Palak et al., 2014) | | | | X | | |
| (Devika et al., 2014) | | | X | X | | |
| (Fahimnia et al., 2015a) | X | X | | X | | |
| (Fahimnia et al., 2015b) | X | X | | X | | |
| (Ben-Salem et al., 2015) | X | | | X | | |
| (Pan and Li, 2015) | X | X | | X | | |
| (Bing et al., 2015) | | | X | X | | |
| Our study | X | X | X | X | X | X |

## 2.3 Problem Definition

In the scenarios that follow, we shall study a infinite-horizon single-item system with returns subject to a cap-and-trade program and to a minimal recovery strategy. A cap-and-trade mechanism allows carbon-emitting companies to buy carbon credits up to a maximum when they have exceeded their emission cap, and to sell up to a maximum of allowances. In particular, a loose emission-cap or a company stopping production to trade its allowances would result in a firm with sufficient credits to not reduce its emissions and still get benefits from the sale of allowances. To prevent those scenarios, the sale of carbon credits is then only possible when the company achieved a $\beta$-emission reduction from the previous period. We also considered a minimal recovery constraint at each period where remanufactured returns must reach a minimal level ($\alpha$). We consider this as a major managerial strategic consideration in the scenario in which remanufacturing is more expensive than manufacturing. If company decisions are merely cost-driven, remanufacturing obviously will not occur. In this case, the legislation introduces product recovery by force.

The system illustrated in Figure 2.2 is an infinite-horizon, periodic-review process modeled in discrete time. It considers two finite-capacity stocking points, namely remanufacturable inventory and serviceable inventory. The inventory holding costs per unit per period are $h^R$ (remanufacturable) and $h^S$ (serviceable). The environmental impact of holding activities is not considered since it is considered negligible compared to the impact of manufacturing and remanufacturing.

Remanufacturable inventory is replenished by returns. All recovered products meet quality standards for reuse. The remanufacturing process has limited capacity and a single-period lead-time, which increases the serviceable inventory level at the end of the period. There are economic and environmental contributions associated to remanufacturing. Serviceable inventory is also replenished as products are manufactured. Like remanufacturing, the manufacturing process has limited capacity and a single-period lead-time and also raises the inventory

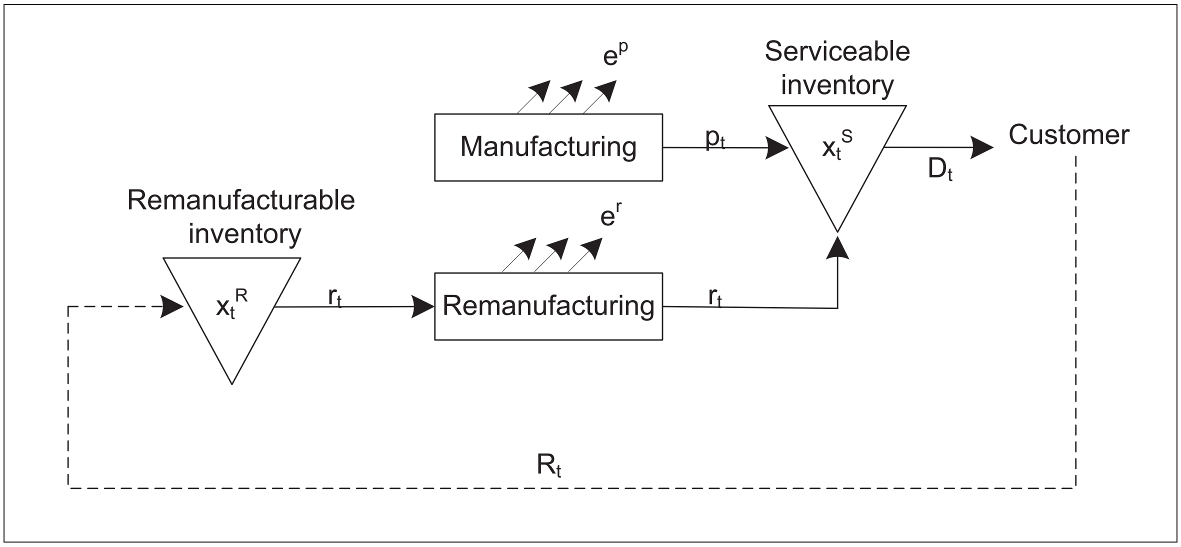


Figure 2.2 Remanufacturing system

level at the end of the period. There is a variable manufacturing cost per product and an amount of emissions generated per quantity produced.

### 2.3.1 Sequence of Events

We considered MDPs is an effective technique to obtain the optimal optimal policy of sequential decision making problems in the presence of uncertainty. Therefore, the problem presented is modeled as a MDP with system dynamics illustrated by Figure 2.3. More specifically, the timing of events is described as follows. At the beginning of a period $t$, inventories are updated and remanufacturing and manufacturing decisions are made. We consider allowances are traded instantaneously. Then, monitored throughout the period, demand $D_t$ and returns $R_t$ are presumed to be independent, non-negative, discrete random variables with probability distributions $\phi(i) = \Pr[D_t = i]$ and $\phi(j) = \Pr[R_t = j]$ respectively. Demand and returns rates remain unchanged from one period to the next. Furthermore, demand that cannot be fulfilled immediately is backordered up to a maximum $\kappa^v$, above which sales are lost. In addition, disposal of returns is considered only when remanufacturable inventory capacity is exceeded, since disposal is relevant only when return rates are excessive (Teunter and Vlachos, 2002). Holding costs, penalties (lost sales and backorders), as well as environmental impact are considered at the end of the period. The objective is to characterize the policy that will determine for each period the quantities of product to remanufacture ($r_t$) and manufacture ($p_t$) that minimize the total cost while complying with an emission-trading program.

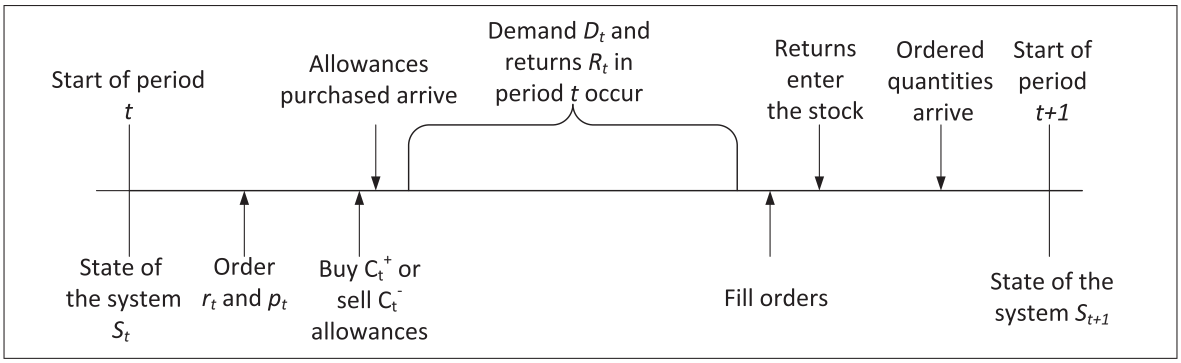


Figure 2.3 Timing of events

The associated model is described below. Remaining notation used throughout this paper is the following:

**Parameters:**

| | |
|---|---|
| $\kappa^r$ | Remanufacturing capacity |
| $\kappa^p$ | Manufacturing capacity |
| $\kappa^S$ | Serviceable inventory capacity |
| $\kappa^{aR}$ | Recoverable inventory capacity |
| $\kappa^v$ | Maximum amount of backlog allowed |
| $\kappa^e$ | Maximum amount of credits allowed to buy or to sell |
| $\phi(i)$ | $\Pr[D_t = i]$ |
| $\phi(j)$ | $\Pr[R_t = j]$ |
| $E^c$ | Emission cap |

$e^r$ Carbon emissions per remanufactured product

$e^p$ Carbon emissions per manufactured product

$\alpha$ Minimal recovery factor

$\beta$ Minimal emission reduction between period $t$ and $t+1$ to allow selling of carbon credits at period $t$

**Costs:**

$h^S$ Serviceable holding cost per unit per period

$h^R$ Remanufacturable holding cost per unit per period

$v$ Shortage cost per unit per period

$C_r$ Remanufacturing cost per unit

$C_p$ Manufacturing cost per unit

$C_d$ Disposal cost per unit

$C_{ls}$ Lost sale cost per unit

$C_c^+$ Carbon credit purchase price

$C_c^-$ Carbon credit selling price

**Random Variables:**

$D_t$ Stochastic demand in period $t$

$R_t$ Stochastic returns in period $t$

**Decision Variables:**

$p_t$ Quantity of products manufactured in period $t$

$r_t$ Quantity of products remanufactured in period $t$

$C_t^+$ Carbon credits bought in period $t$

$C_t^-$ Carbon credits sold in period $t$

**State Variables:**

$x_t^R$ Remanufacturable inventory level at the beginning of period $t$

$x_t^S$ Serviceable inventory level at the beginning of period $t$

$e_t$ Emissions held at the beginning of period$t$

$\varpi_t$ Emissions generated at period *t-1*

### 2.3.2 State Space and Action Space

The system state is characterized by the remanufacturable inventory level $x_t^R$, the serviceable inventory level $x_t^S$, the number of carbon credits $e_t$ possessed by the company, and the number of emissions generated at the end of the previous period $\varpi_t$. The state space $\mathscr{S}$ is thus defined as $\{[0, \quad k^S] \times [0, \quad k^{aR}] \times [0, \quad E^c] \times [0, \quad E^c + \kappa^e]\}$. The state of the system at the beginning of a period is therefore given as: $s_t := (x_t^S, x_t^R, e_t, \varpi_t)$.

The action space $\mathscr{A}(s_t)$ corresponds to the set of all possible decisions $d_{s_t}(\pi)$ that satisfy the constraints, given the system state $s_t$. These are a combination of the decisions to manufacture $[0, \quad \kappa^p]$, to remanufacture $[0, \quad \kappa^r]$ and to buy or sell allowances $[0, \quad \kappa^e] \times [0, \quad \kappa^e]$. Decisions are generally specified for each state $s_t \in \mathscr{S}$ according to a policy $\pi$. For a given problem, there might be several possible policies denoted by the set $\Pi$. We consider a stationary policy only. Decisions are thus determined by the current state of the system, regardless of time.

### 2.3.3 State Transition

Transition from state $s_t$ to state $s_{t+1}$ will depend on the set of decisions $d_{s_t}(\pi) := (p_t, r_t, C_t^+, C_t^-)$ made according to the policy $\pi$, as well as on the random variables (demand and returns) associated with their corresponding probabilities. For the system under study, determination of the transition probability matrix is defined as the joint probability of demand and returns, that is, $P_\pi(s_t, s_{t+1}) = \sum_{j=0}^{\infty} \sum_{i=0}^{\infty} \Pr[D_t = i] \Pr[R_t = j]$. The transition from state $s_t$ to state $s_{t+1}$, where $s_{t+1} := (x_{t+1}^S, x_{t+1}^R, e_{t+1}, \varpi_{t+1})$, is given by Equations (2.1) to (2.4).

Expression (2.1) denotes the remanufacturable inventory level at the beginning of period $t+1$. It is given by the inventory level at the beginning of period $t$ minus the remanufactured amount plus the return observed during period $t$.

$$x_{t+1}^{R} = x_{t}^{R} + j - r_{t} \tag{2.1}$$

The serviceable inventory level at the beginning of period $t+1$ is given by Expression (2.2). It is defined by the manufactured and remanufactured quantities plus the maximum of the serviceable inventory level during period $t$ minus the demand $i$ and the backorder limit $\kappa^{v}$.

$$x_{t+1}^{S} = \max\{x_{t}^{S} - i, -\kappa^{v}\} + p_{t} + r_{t} \tag{2.2}$$

We define the emission level or the emission bank as the environmental stability of the system given by the number of carbon credits that can still be used by the system. The emissions level, $e_{t+1}$, is obtained from the quantity of emission produced during the previous period $e_t$ minus that associated with the actions taken $\eta_t(\cdot)$ plus the quantity of allowances bought and sold $(C_t^{+}, C_t^{-})$.

$$e_{t+1} = e_{t} - \eta_{t}(p_{t}, r_{t}) - C_{t}^{-} + C_{t}^{+} \tag{2.3}$$

To model if a $\beta$-emission reduction has be achieved, we measure the environmental impact during the previous period. The term $\varpi_{t+1}$ is equivalent to the emissions generated during the previous period $t$.

$$\varpi_{t+1} = \eta_t(p_t, r_t) \tag{2.4}$$

### 2.3.4 Reward function

Let $f_\pi(x_t^S, x_t^R, e_t, \varpi_t)$ denote the expected cost when the system is operated under the policy $\pi \in \Pi$ given the state of the system $(x_t^S, x_t^R, e_t, \varpi_t)$ at the beginning of period $t$. The objective is to determine the policy $\pi \in \Pi$ that minimizes the total expected cost while operating within the constraints. The total cost is given by Expression (2.5). This is defined in terms of 1) production costs; 2) holding costs and penalties; and 3) allowance trading.

$$f_\pi(x_t^S, x_t^R, e_t, \varpi_t) = \underbrace{\delta(p_t) + \gamma(r_t)}_{\text{production costs}} + \underbrace{H(x_t^R, r_t) + L(x_t^S, r_t, p_t)}_{\text{holding costs and penalties}} + \underbrace{\rho(p_t, r_t, C_t^+, C_t^-)}_{\text{allowance trading}} \tag{2.5}$$

#### Production costs

Manufacturing and remanufacturing costs, consider a quantity-related cost.

$$\delta_t(p_t) = C_p p_t \tag{2.6}$$

$$\gamma_t(r_t) = C_r r_t \tag{2.7}$$

#### Holding costs and penalties

Let $H_t(x_t^R, r_t)$ denote the expected holding and disposal costs for remanufacturable inventory. A holding cost $h^R$ per unit will be charged for all returned products remaining at the inventory at the end of the period. In addition, if the remanufacturable inventory level exceeds its capacity $\kappa^{aR}$, surplus products are disposed of at a cost $C_d$ per unit.

$$\begin{aligned} H_t(x_t^R, r_t) &= h^R \sum_{j=0}^{\kappa^{aR}+r_t-x_t^R} (x_t^R + j - r_t)\phi(j) \\ &+ C_d \sum_{j>\kappa^{aR}+r_t-x_t^R}^{\infty} (x_t^R + j - (\kappa^{aR} + r_t))\phi(j) \end{aligned} \tag{2.8}$$

Let $L_t(x_t^S, r_t, p_t)$ denote the expected holding costs and penalties for serviceable products. This considers: 1) the holding cost $h^S$ that is charged to all serviceable products remaining at the inventory at the end of the period; 2) the expected shortage cost $v$ charged to the sum of back-order; and 3) the expected cost of lost sales given by a lost sale penalty $C_{ls}$ associated with the unfilled demand going above $\kappa^v$.

$$\begin{aligned} L_t(x_t^S, r_t, p_t) &= h^S \sum_{i=0}^{x_t^S} [x_t^S - i + p_t + r_t]^+ \phi(i) \\ &+ v \sum_{i>x_t^S}^{x_t^S+\kappa^v} (i - x_t^S)\phi(i) + C_{ls} \sum_{i>x_t^S+\kappa^v}^{\infty} (i - x_t^S)\phi(i) \end{aligned} \tag{2.9}$$

Where $[x]^+ = \max\{x, 0\}$.

### Environmental cost

Let $\rho(p_t, r_t, C_t^+, C_t^-)$ denote the cost for the emissions generated. The first term represents the expected cost of the emissions generated. The second and third terms represent the expected quantity of allowances to buy or to sell, respectively.

$$\rho(p_t, r_t, C_t^+, C_t^-) = C_c^+ C_t^+ - C_c^- C_t^- \tag{2.10}$$

Where $\eta_t(x_t^S, x_t^R, p_t, r_t)$ defines the total amount of emissions generated over period $t$ for the set of activities $(p_t, r_t)$. Hence,

$$\eta_t(p_t, r_t) = e^p p_t + e^r r_t \tag{2.11}$$

The environmental impact of an inventory policy is given by $E_\pi(x_t^S, x_t^R, e_t, \varpi_t)$ which defines the expected amount of emissions generated and sold over the long term under a policy $\pi$, given the state $(x_t^S, x_t^R, e_t, \varpi_t)$. The emissions bought were omitted since they are already considered in the emissions generated.

$$E_\pi(x_t^S, x_t^R, e_t, \varpi_t) = \eta_t(p_t, r_t) + C_t^- \tag{2.12}$$

Decisions are subject to the following constraints. Manufacturing and remanufacturing orders must not exceed either production capacities or inventory levels.

$$r_t \leq \min\{x_t^R, \kappa^r\} \tag{2.13}$$

$$p_t \leq \kappa^p \tag{2.14}$$

Replenishment quantities must be integers and greater than their required minimum.

$$p_t \geq 0 \quad \text{and integer} \tag{2.15}$$

$$r_t \geq \alpha x_t^R \quad \text{and integer} \tag{2.16}$$

Inventory capacities must be respected.

$$x_t^R \leq \kappa^{aR} \tag{2.17}$$

$$x_t^S \leq \kappa^S \tag{2.18}$$

The number of emissions to trade must be an integer and less than the maximum permitted. Moreover, the set of constraints (2.21) to (2.22) ensures it is possible to sell allowances only when the emissions from the previous period were reduced at least by $\beta$. The parameter $\beta$ denotes the minimal reduction of emissions and $M$ is a large positive constant.

$$C_t^+ \leq \kappa^e \tag{2.19}$$

$$C_t^- \leq \kappa^e y \tag{2.20}$$

$$\frac{\varpi_t - \varpi_{t+1}}{\varpi_t} \geq \beta + M(y-1) \tag{2.21}$$

$$y \geq 0, y \leq 1 \quad \text{and integer} \tag{2.22}$$

$$C_t^+, C_t^- \geq 0 \quad \text{and integer} \tag{2.23}$$

Emissions banked at the end of each period must be lower than the emissions cap.

$$e_t \leq E^c \tag{2.24}$$

Finally, state variables $x_t^R$ and $e_t$ must be non-negative.

$$x_t^R \geq 0, e_t \geq 0 \tag{2.25}$$

## 2.4 Solution Approach and Inventory Policy Characterization Methodology

The mathematical model was validated in a preliminary study, in which we obtained the same results that Ahiska and King (2010). For this purpose, we assigned zero emissions for each activity and we set the minimal remanufacturing requirement to zero. The MDP model was programmed in Matlab™and run on an Intel®Core™i7 2.20 GHz PC.

The proposed study is used to determine a) the importance of the inventory policy in satisfying environmental constraints and b) the effect of the emission-cap and carbon credit prices on the inventory policy. The proposed approach consist of two parts. The first part of the study demonstrates the role that could play inventory control under product remanufacturing and carbon emissions constraints. The second part is dedicated to the new policy definition.

In the first part, we derive the optimal production strategy for a conventional scenario by solving the MDP. Henceforth, conventional denotes the absence of cap-and-trade scheme and green refers to a case where a cap-and-trade scheme is applied. Based on the observation of the optimal replenishment strategy, we define the structure and parameter values of the inventory policy. We measure the performance of the inventory policy in terms of the deviation from the long-term cost given by Expression (2.5). We demonstrate how inventory policies help to meet environmental targets set by the cap-and-trade scheme. To this end, given a system subject to a cap-and-trade scheme we apply a conventional policy. Then, we measure the economic and environmental performance based on Expressions (2.5) and (2.12), respectively. Finally, we determine the gain or loss in economic and environmental terms from applying a green against a conventional inventory policy.

In the second part of this study, for a system subject to a cap-and-trade scheme we derive the optimal production and carbon management strategy and characterize the structure of decisions. The performance of the inventory policies is measured as before, in terms of the deviation from the long-term cost (Expression (2.5)). We repeat the proposed approach by permuting underlying environmental parameters (the emission cap, the allowance price) and the manufacturing cost.

## 2.5 Experimentation

The inventory model developed previously can be applied to any system as long as it possesses the characteristics described in Section 2.3. Based on our research objective, we chose to illustrate the applicability of the model and the proposed approach using the following numerical example.

### 2.5.1 Numerical Example

As shown in Table 2.2, emissions per unit of product are 50% lower for remanufacturing than for the manufacturing process. However, we assume in this example that remanufacturing is the most expensive process, since all collection activities are included in the cost. This will be the case particularly when the return flow is ill-defined and recovering of end-of-life products is expensive, or when recovered items need a pre-treatment to standardize material quality before beginning remanufacturing. The case in which remanufacturing is cheaper is also studied. This situation is expected to become widespread in the foreseeable future, due to increases in return-channel efficiency. The values used in the basic scenario are presented in Table 2.2.

Table 2.2 Cost and emission factors

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $C_p$ | \$90/tonne | $C_c^+$ | \$1.36/t$CO_2$ |
| $C_r$ | \$130/tonne | $C_c^-$ | \$1.32/t$CO_2$ |
| $C_d$ | \$0/tonne | $e^p$ | 2t$CO_2$/tonne |
| $h^S$ | \$15/tonne | $e^r$ | 1t$CO_2$/tonne |
| $h^R$ | \$1.6/tonne | $E^c$ | 8t$CO_2$ |
| $v$ | \$ 115/tonne | $\kappa^e$ | 2t$CO_2$ |
| $C_{ls}$ | \$179/tonne | $\alpha$ | 0.1 |
| $\beta$ | 0.2 | | |

The aluminum sector is an energy- intensive industry and, therefore, it is frequently subject to meet environmental targets (Hong et al., 2012). Given the importance of the aluminum industry, we considered data on the aluminum industry to illustrate the applicability of our model.

The London Metal Exchange and rapports such as the one presented in the MetalMiner by Burns (2015) help us determine production costs. Ultimately, for carbon footprints we considered data from the Intergovernmental Panel on Climate Change. The remaining parameters such as demand and returns, shown in Table 2.3, were inspired on the work of Ahiska and King (2010) and adapted to the size of our model. We considered then demand and returns to be distributed per period as follows:

$$\phi(i)=\Pr[D_t = i] = \begin{cases} \frac{i}{20}, & 1 \leq i \leq 4 \\ \frac{9-i}{20}, & 4 < i \leq 8 \\ 0, & \text{otherwise} \end{cases}$$

$$\phi(j)=\Pr[R_t = j] = \begin{cases} \frac{j+1}{9}, & 0 \leq j \leq 2 \\ \frac{5-j}{9}, & 2 < j \leq 4 \\ 0, & \text{otherwise} \end{cases}$$

Table 2.3 Parameters

| Parameter | Value |
|---|---|
| $\kappa^p$ | 50 tonnes |
| $\kappa^r$ | 20 tonnes |
| $\kappa^S$ | 8 tonnes |
| $\kappa^{aR}$ | 4 tonnes |
| $\kappa^v$ | 1 tonne |

To characterize the cap and trade scheme our numerical examples relied on the European Emission Trading and the California Cap-and-Trade scheme. Based on these sources, we set the range of allowance selling prices for the purposes of the study from \$1.36/t$CO_2$ to \$102.00/t$CO_2$. These values allow us to simulate the current situation to a foreseen future where the price is extremely high. Considering the production cost and the allowance price 20 scenarios were created. These scenarios were repeated for each emission cap tested. Table 2.4 summarizes the parameters used for each scenario.

Table 2.4 Numerical examples

| Scenario | $C_p$ | $C_r$ | $C_c^+$ | $C_c^-$ | Scenario | $C_p$ | $C_r$ | $C_c^+$ | $C_c^-$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 90 | 130 | 1.36 | 1.32 | 11 | 130 | 90 | 1.36 | 1.32 |
| 2 | 90 | 130 | 6.8 | 6.6 | 12 | 130 | 90 | 6.8 | 6.6 |
| 3 | 90 | 130 | 13.6 | 13.19 | 13 | 130 | 90 | 13.6 | 13.19 |
| 4 | 90 | 130 | 20.4 | 19.79 | 14 | 130 | 90 | 20.4 | 19.79 |
| 5 | 90 | 130 | 27.2 | 26.38 | 15 | 130 | 90 | 27.2 | 26.38 |
| 6 | 90 | 130 | 34 | 32.98 | 16 | 130 | 90 | 34 | 32.98 |
| 7 | 90 | 130 | 40.8 | 39.58 | 17 | 130 | 90 | 40.8 | 39.58 |
| 8 | 90 | 130 | 61.2 | 59.36 | 18 | 130 | 90 | 61.2 | 59.36 |
| 9 | 90 | 130 | 81.6 | 79.15 | 19 | 130 | 90 | 81.6 | 79.15 |
| 10 | 90 | 130 | 102 | 98.94 | 20 | 130 | 90 | 102 | 98.94 |

### 2.5.2 Baseline Scenarios

In the baseline scenario, we considered the system without taking into account its GHG emissions of manufacturing and remanufacturing activities. Then, the inventory policy is characterized based on manufacturing decisions. The optimal cost and GHG emissions in this case do not depend on the emission cap ($E^c$), and since this scenario does not consider trading carbon credits, the values of $C_c^+$ and $C_c^-$ have no impact on the total cost. We examined two cases, as described below.

#### 2.5.2.1 Case I. Remanufacturing is more expensive, but greener than manufacturing

In the baseline scenario the inventory model works on a cost-reduction basis rather than a greening basis. Hence, in the first case manufacturing is the preferred process since it is the less expensive. The set of decisions could be characterized through a policy of structure $(S^a, \bar{q}^a)$, with an average deviation of 0.01% from the optimal cost.

A $(S^a, \bar{q}^a)$ can be seen as a restricted base-stock policy, where the maximal quantity to order is set to a maximum level. This policy works as follows: The remanufacturable inventory is noted at the beginning of the period, and the minimal quantity $\lceil \alpha x_t^R \rceil$ necessary to satisfy the minimal recycling rate constraint is remanufactured. The serviceable inventory level is then noted, and if $x_t^S$ is less than the order-up to level $S^a$ the lesser between the quantity necessary to reach the order-up-to level $S^a$ (i.e. $S^a - x_t^S - r_t$) and a fixed quantity $\bar{q}^a - r_t$ is manufactured. Otherwise, no manufactured is required. Decisions resulting from the above policy are summarized as follows:

$$r_t = \lceil \alpha x_t^R \rceil \tag{2.26}$$

$$p_t = \begin{cases} \min\{\bar{q}^a - r_t, S^a - x_t^S - r_t\}, & x_t^S + r_t < S^a \\ 0, & \text{otherwise} \end{cases} \tag{2.27}$$

In this scenario, the parameter values correspond to $S^a = 9$ and $\bar{q}^a = 7$. Using Expressions (2.5) and (2.12) respectively, the optimal cost of the baseline scenario is \$589.41 with an environmental impact of 7.6t$CO_2$.

#### 2.5.2.2 Case II. Remanufacturing is less expensive and greener than manufacturing

In the second case, in which manufacturing is the more expensive process, remanufacturing is preferred. Decisions are characterized by a policy of structure $(S^b, \bar{q}^b)$, which is similar to $(S^a, \bar{q}^a)$, differing only in terms of the remanufacturing order size.

The remanufacturable and serviceable inventory levels are noted at the beginning of a period. Under a $(S^b, \bar{q}^b)$ policy, if $x_t^S$ is less than the order-up to level $S^b$ and the required amount to reach $S^b$ is greater than $\bar{q}^b$, the lesser of values $\bar{q}^b$ and $x_t^R$ is remanufactured. Considering the manufacturing actions, the quantity to manufacture is $\bar{q}^b - r_t$ units. Whether the difference between serviceable inventory $x_t^S$ and the order-up to level $S^b$ is less than $\bar{q}^b - r_t$, it is the lesser of $S^b - x_t^S$ and $x_t^R$ that is remanufactured. If $x_t^S$ is still less than $S^b$, then $S^b - x_t^S - r_t$ units are manufactured. With an optimal cost of \$639.95 and an environmental impact of 6.65t$CO_2$, this characterization has an expected deviation of 0.05% from the optimal cost. The parameter values of the policy $(S^b, \bar{q}^b)$ correspond to the values $(9,7)$, as in case I. The $(S^b, \bar{q}^b)$ policy is summarized as follows:

$$r_t = \begin{cases} \min\{x_t^R, \bar{q}^b\}, & x_t^S < S^b, \quad S^b - x_t^S \geq \bar{q}^b \\ \min\{x_t^R, S^b - x_t^S\}, & x_t^S < S^b \\ 0, & \text{otherwise} \end{cases} \tag{2.28}$$

$$p_t = \begin{cases} \bar{q}^b - r_t & x_t^S + r_t < S^b, \quad S^b - x_t^S \geq \bar{q}^b \\ S^b - x_t^S - r_t, & x_t^S + r_t < S^b \\ 0, & \text{otherwise} \end{cases} \tag{2.29}$$

We thus see that when the environmental impact is not considered, the structure of the inventory policy is easy to recognize, and can be expressed using a few parameters.

### 2.5.3 Inventory control under carbon emissions constraints

In the following, we evaluate the effect of using the inventory policies determined in section 2.5.2 in a system under carbon emission constraints.

We evaluate the impact of the emission-cap on the total cost of the system. We tested four different emission cap values ($E^c$=2t$CO_2$, 3t$CO_2$, 4t$CO_2$, 5t$CO_2$) based on the GHG emissions generated in the baseline scenario. In addition, we explored the impact of carbon credit prices on replenishment decisions. Only one parameter was changed at the time. We focused on the two cases described above.

clicours.com

#### 2.5.3.1 Case I. Remanufacturing is more expensive, but greener than manufacturing

In the baseline scenario, decisions are driven by manufacturing and remanufacturing costs. Nevertheless, as the carbon price increases, the manufacturing and remanufacturing cost increases as well. Figure 2.4 shows the relation between the production cost and the lost sale cost against the allowance price. In fact, manufacturing is only less expensive than remanufacturing when allowance prices are below \$40/t$CO_2$.

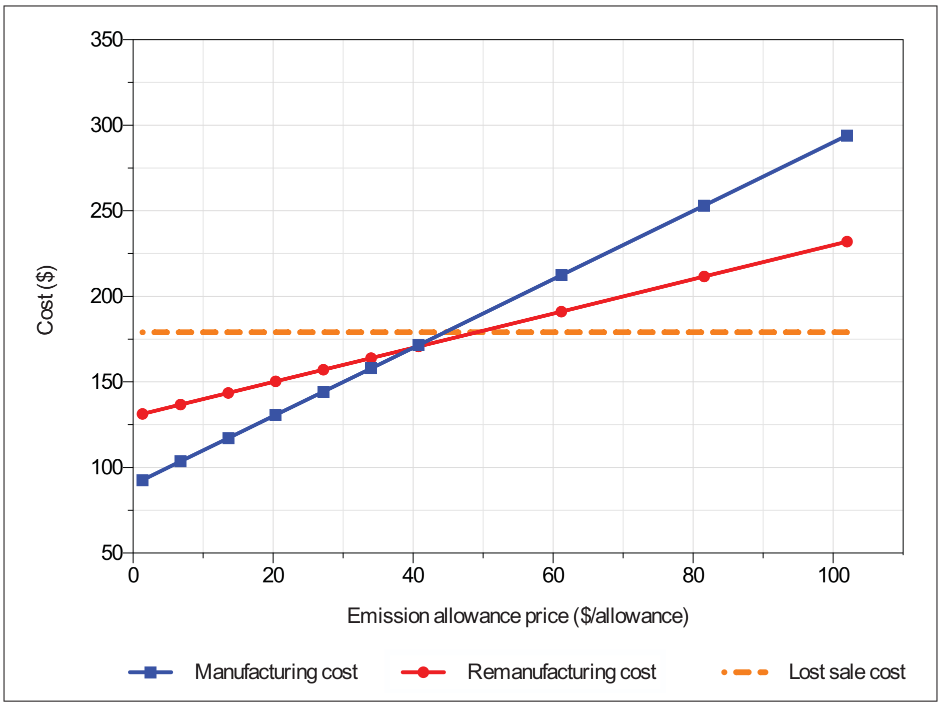


Figure 2.4 Relation between operational costs case I

Figure 2.5 shows the comparison between the optimal cost and the cost obtained when baseline scenario policies are used. We thus observe that the difference between the cost of using baseline policies and the optimal cost, increases the most when the carbon price makes remanufacturing less expensive than manufacturing. The company of course in the baseline policy still favors manufacturing even if its cost exceeds the cost of remanufacturing. In addition to this, accounting for the emissions gives the company the opportunity to enjoy a financial benefit.

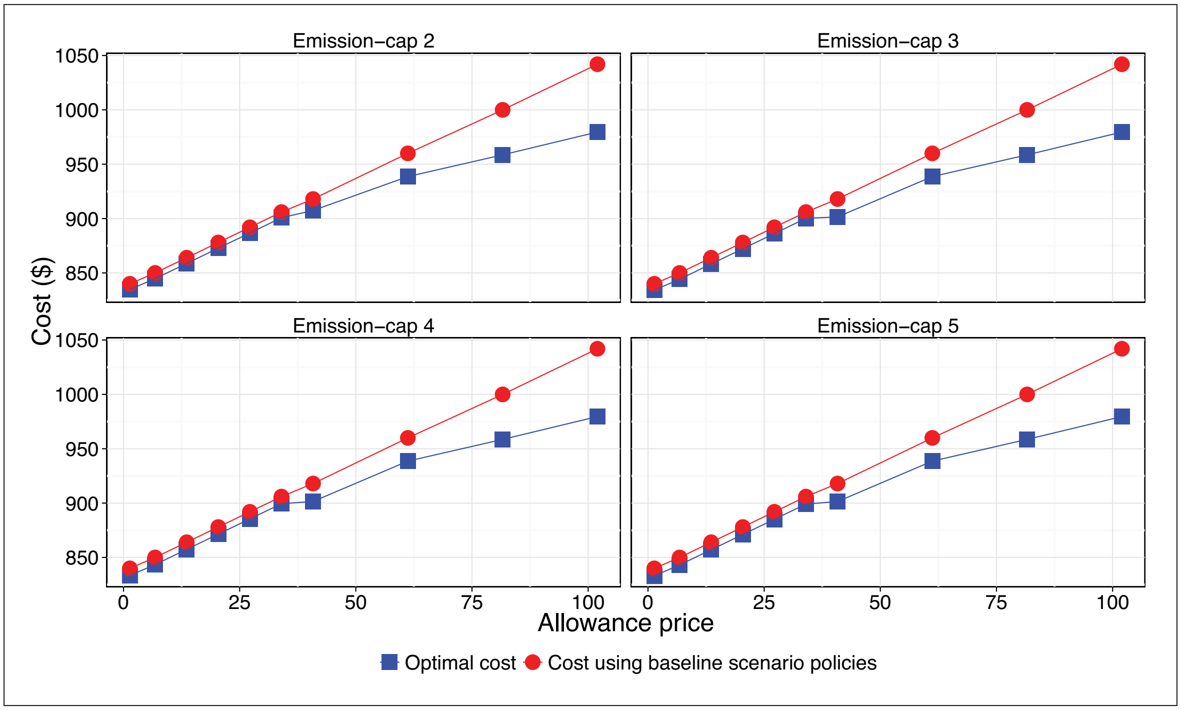


Figure 2.5 Deviation from optimal cost using baseline policies under cap-and-trade in case I

In average, the use of a baseline policy increased the cost by 1.88% with a standard deviation of 1.86.

#### 2.5.3.2 Case II. Remanufacturing is less expensive and greener than manufacturing

Figure 2.6 shows the increase in manufacturing and remanufacturing cost along with the allowance price. Manufacturing is always more expensive than remanufacturing.

As it can be seen in Figure 2.7, the difference in cost (on average 1.18% per period with a standard deviation of 0.75) between the policies is due to manufacturing being stopped as it reaches the lost sales cost. However, decreasing the service level is not a viable managerial option. Since the most cost-efficient process is also the most enviro-friendly, applying a baseline policy in this scenario would remain feasible only if the order size were limited to whatever is allowed by the emissions credits available.

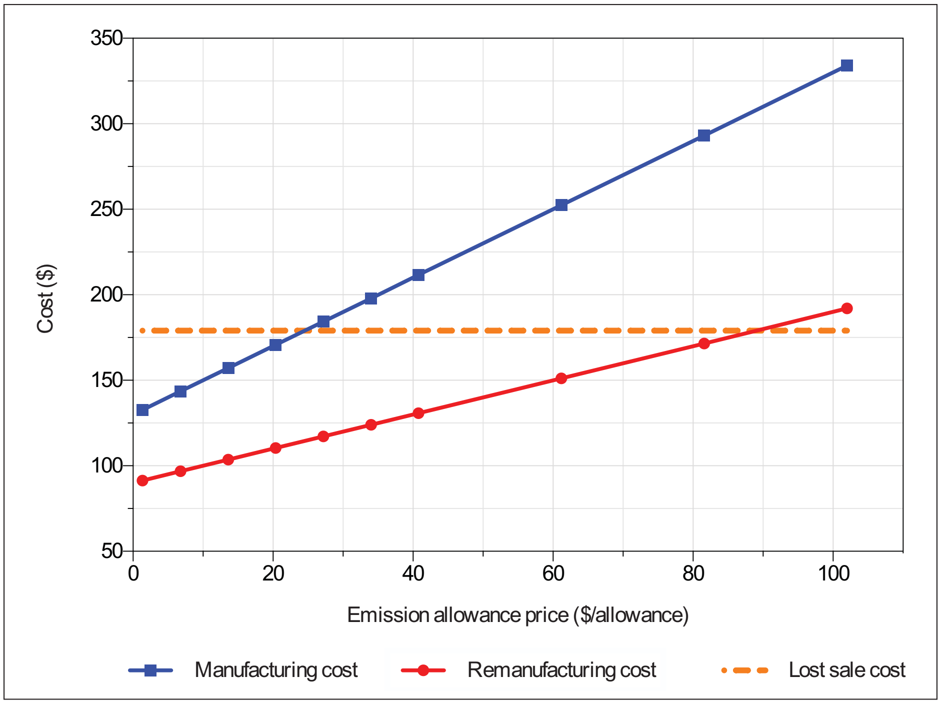


Figure 2.6 Relation between operational costs case II

### 2.5.4 Inventory policies under the cap-and-trade scheme

In this section, we focus on inventory policy structure characterization under joint product recovery and cap-and-trade constraints. The effect of the emission cap and the allowance price would be studied in a further section. To the best of our knowledge, there are no studies related to this specific subject although its importance. Indeed, many organizations are subject to both carbon emission reduction and product recovery legislations. As for the previous experiments, we propose to analyze the inventory policies in the two cases.

#### 2.5.4.1 Case I. Remanufacturing is more expensive, but greener than manufacturing

In order to analyze the decisions, we derived classification trees using the CART algorithm implemented on Tree, an R package written by Ripley (2016). Figure 2.8 shows the classification tree for manufacturing. The remanufacturable inventory level and the number of emissions held

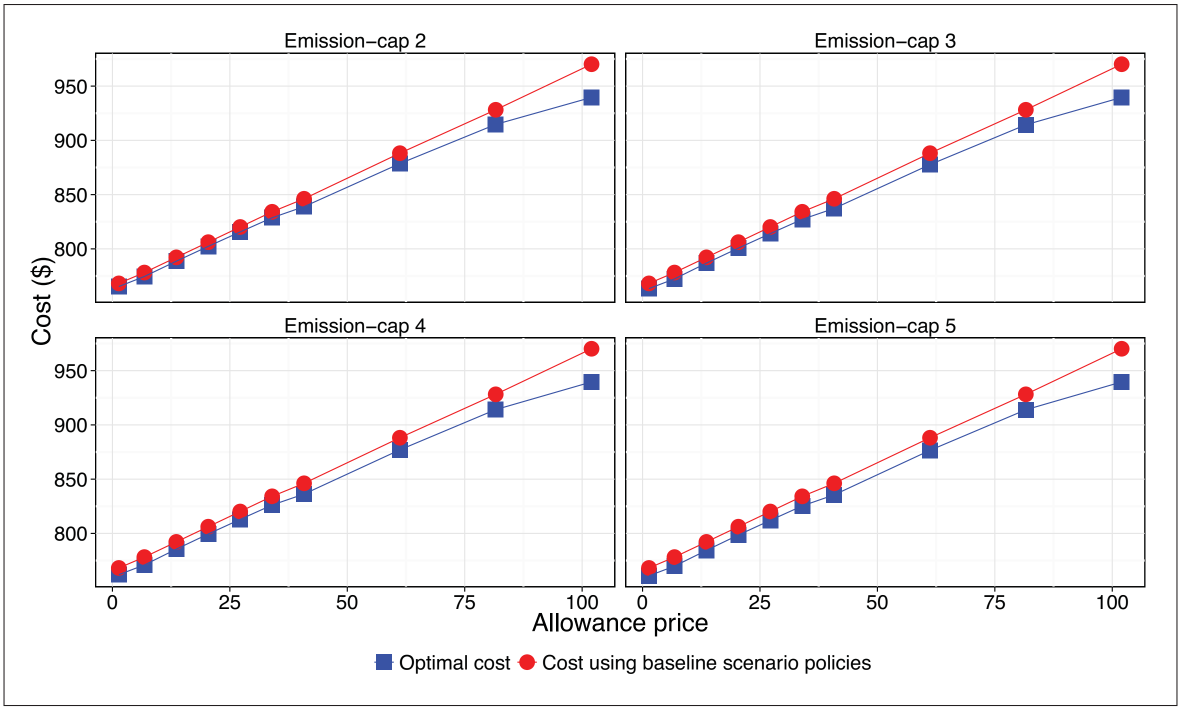


Figure 2.7 Deviation from optimal cost using baseline policies under cap-and-trade in case II

in the system are the states most influencing the size of the manufacturing lot. In particular, the manufacturing lot size would increase as more emissions are held in the system.

Figure 2.9 illustrates the classification tree for remanufacturing. Remanufacturing lot sizes besides being correlated to the remanufacturable inventory, it is also highly correlated to the serviceable inventory.

The information obtained by the classification trees helped to generate the inventory policies. The structure of the policy might be described as follows. When manufacturing is cheaper than remanufacturing, the decisions made can be characterized by two policies, namely $(S^c, \bar{q}^c)$ and $(\varepsilon')$. The choice between these is driven by the allowance price. Under a $(S^c, \bar{q}^c)$ policy, both manufacturing and remanufacturing are practiced. However, as the carbon cost increases, the policy shifts to $(\varepsilon')$, under which remanufacturing is only used to guarantee the minimal remanufacturing proportion $\alpha$. Hence,

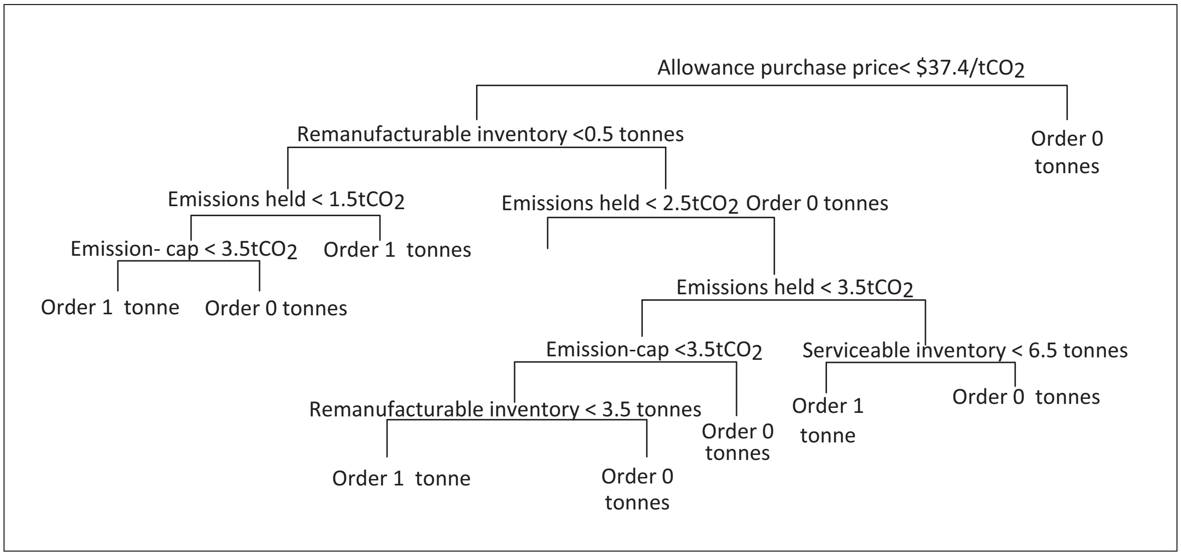


Figure 2.8 Classification tree of manufacturing strategy in case I. Classification error= 9.59%

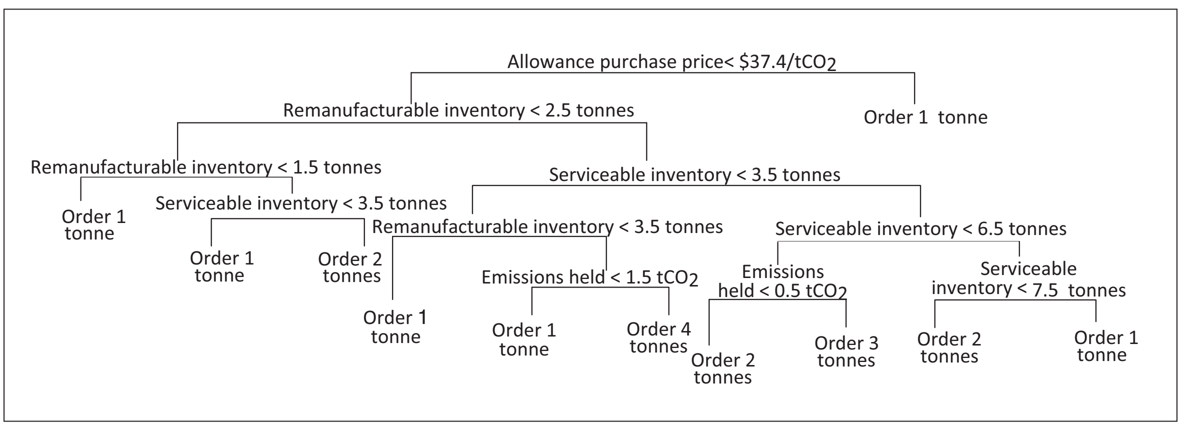


Figure 2.9 Classification tree of remanufacturing strategy in case I. Classification error= 9.84%

$$r_t = \lceil \alpha x_t^R \rceil \tag{2.30}$$

$$p_t = 0 \tag{2.31}$$

In contrast, the $(S^c, \bar{q}^c)$ policy works as follows. The serviceable inventory level $x_t^S$ and the carbon credit level $e_t$ are noted at the beginning of the period. If $x_t^S$ is less than the order-up to level $S^c$, and the difference is larger or equal than $\bar{q}^c$, the lesser of quantities $\bar{q}^c$ and $x_t^R$ is remanufactured. However, if $e_t$ is equal to the emission cap, all $x_t^R$ inventory is remanufactured. Whether the quantity to reach the order-up to level $S^c$ is less than $\bar{q}^c$, the lesser of $S^c - x_t^S$ and $x_t^R$ is remanufactured. Nevertheless, if $S^c - x_t^S$ is less than the minimal quantity $\varepsilon$, $\varepsilon$ units will be remanufactured.

The decision to manufacture is made as follows: If the serviceable inventory level $x_t^S$ noted at the beginning of the period plus the remanufactured quantity $r_t$ is less than the reorder level $S^c$, the emissions banked are less than the emission cap, and $S^c - x_t^S$ is greater than $\bar{q}^c$, then $\bar{q}^c - r_t$ units are manufactured. However, if $e_t \geq E^c$, then $q^c$ units are manufactured (if justified by the amount of emissions), otherwise no units are manufactured. If the difference between the order-up to level $S^c$ and the current serviceable inventory is less than $\bar{q}^c$, $\min\{S^c - x_t^s - r_t, \lfloor \frac{e_t + \kappa^e - e^R r_t}{e^p} \rfloor\}$ units are manufactured.

The quantity $\varepsilon$ denotes either the minimal quantity of items to remanufacture in order to reduce credits $e_t$ to the emission cap $E^c$ or the minimal remanufactured proportion $\alpha$ (the maximum of the two). Considering that the carbon credit selling price is less than the purchase cost, the remanufacturing decision is based preferably on purchasing the maximal possible quantity $\kappa^e$ of carbon credits and using the emissions that exceed the cap $E^c$. Manufacturing and remanufacturing decisions under a $(S^c, \bar{q}^c)$ policy are therefore:

$$r_t = \begin{cases} \min\{x_t^R, \bar{q}^c\}, & x_t^S < S^c, S^c - x_t^S \geq \bar{q}^c, e_t < E^c \\ x_t^R, & x_t^S < S^c, S^c - x_t^S \geq \bar{q}^c, e_t \geq E^c \\ \min\{x_t^R, S^c - x_t^S\}, & x_t^S + \varepsilon < S^c \\ \varepsilon, & \text{otherwise} \end{cases} \tag{2.32}$$

$$p_t = \begin{cases} \bar{q}^c - r_t, & x_t^S + r_t < S^c, S^c - x_t^S \geq \bar{q}^c, e_t < E^c \\ \bar{q}^c, & x_t^S + r_t < S^c, S^c - x_t^S \geq \bar{q}^c, e_t \geq E^c, \chi \geq \bar{q}^c \\ \min\{\lfloor \chi \rfloor, S^c - x_t^S - r_t\}, & x_t^S + r_t < S^c \\ 0, & \text{otherwise} \end{cases} \quad (2.33)$$

with $\chi = \frac{e_t + \kappa^e - e^R r_t}{e^p}$

We can notice that replenishment decisions depended of the emission cap, when there is a surplus on the number of emissions it is preferable to use them firstly in remanufacturing and later in manufacturing instead of selling the credits. Characterization of case I produces a deviation from the optimal cost in the range [0.00%,1.23%], with an average deviation from the optimal cost of 0.12% and a standard deviation of 0.32.

#### 2.5.4.2 Case II. Remanufacturing is less expensive and greener than manufacturing

As in case I, we derived classification trees to illustrate the most significant factors in manufacturing and remanufacturing decision making. Figures 2.10 and 2.11 illustrates the classification trees for manufacturing and remanufacturing, respectively.

As it can be seen, manufacturing is mostly used when it is not possible to remanufacture and the number of emissions level is large. Meanwhile, remanufacturing is highly used when it is possible.

Based on the classification trees previously presented, we could describe the behavior of the inventory policies for Case II. Two inventory policies, namely $(s^d, S^d, r^d, \bar{q}^d)$ and $(\varepsilon')$, characterize the second case, in which remanufacturing is cheaper than manufacturing.

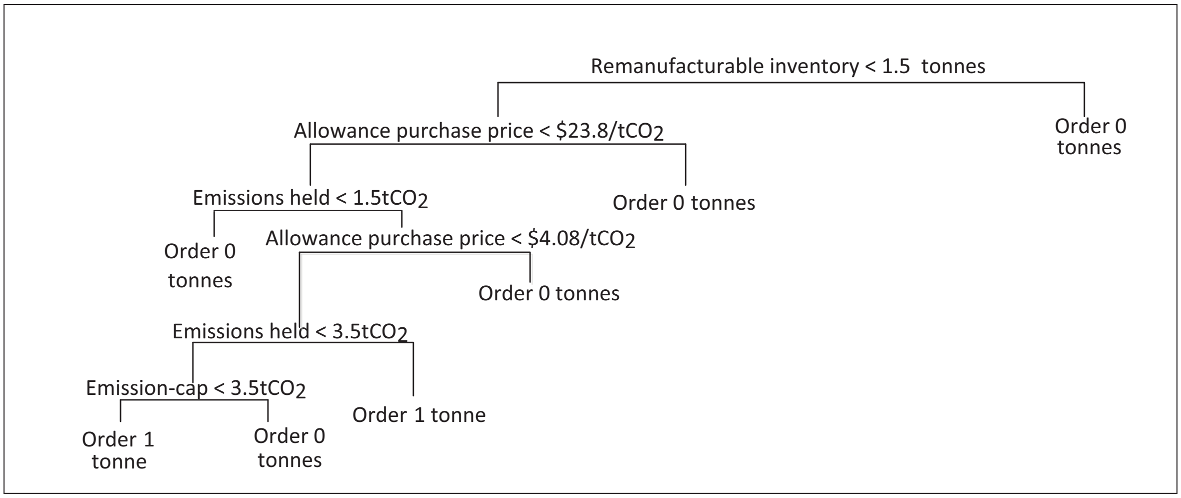


Figure 2.10    Classification tree of manufacturing strategy in case II. Classification error= 1.34%

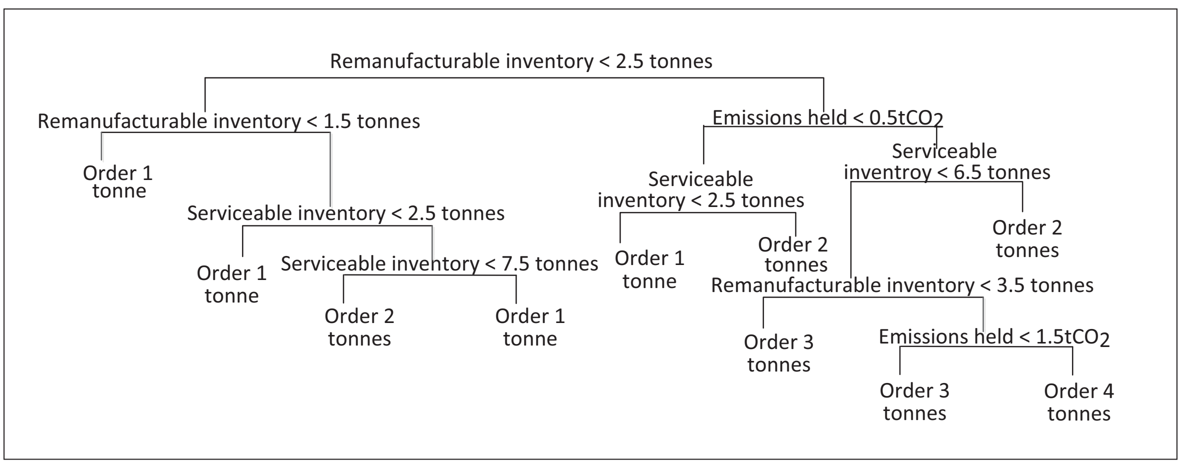


Figure 2.11    Classification tree of remanufacturing strategy in case II. Classification error= 16.74%

Under a $(s^d, S^d, r^d, \bar{q}^d)$ policy, based on the remanufacturable and serviceable inventory levels noted at the beginning of the period, the decision to remanufacture is made as follows: if level $x_t^S$ is less than the reorder level $s^d$, the minimal quantity $\varepsilon$ is remanufactured; however, if $x_t^R$ is greater or equal to $r^d$, $x_t^R$ is remanufactured entirely. On the other hand, if $x_t^S$ is greater than the reorder level $s^d$, $\min\{x_t^R, S^d - x_t^S\}$ units are remanufactured. If $\varepsilon$ is greater than $S^e - x_t^S$, $\varepsilon$ units are nevertheless remanufactured. Manufacturing is performed if $e_t \geq E^c - 1$, in which case $\bar{q}^d - r_t$ units are manufactured, otherwise there is no need for manufacturing. The above policy is thus described as follows:

$$r_t = \begin{cases} x_t^R, & x_t^S < s^d, x_t^R \geq r^d \\ \min\{x_t^R, S^d - x_t^S\}, & x_t^S \geq s^d, \varepsilon < S^d - x_t^s \\ \varepsilon, & \text{otherwise} \end{cases} \quad (2.34)$$

$$p_t = \begin{cases} [\bar{q}^d - r_t]^+, & e_t \geq E^c - 1 \\ 0, & \text{otherwise} \end{cases} \quad (2.35)$$

Where $[x]^+ = \max\{0, x\}$.

The ($\varepsilon'$) policy is the same as in the case I, in which only the minimal proportion $\alpha$ is remanufactured. Characterization of case II results in a deviation of the optimal cost in the range of [0.00%, 0.27%] with an average value of 0.07% and a standard deviation of 0.06.

### 2.5.5 Carbon management strategy

This section seeks to describe the purchase and sale of carbon allowances based on the state of the system, the allowance price, and the emission cap.

#### 2.5.5.1 Case I. Remanufacturing is more expensive, but greener than manufacturing

The factors influencing the most the decisions on the carbon management strategy are the allowance purchase price, the number of emissions held, the remanufacturable inventory level, and the previous period's emissions.

Figures 2.12 shows the classification tree of the allowance purchase strategy. It is clear that allowance purchase decisions are made according to the allowance price, these pair of factors are inversely correlated. While the allowance price is low, it is preferable to purchase the maximum quantity of allowances. On the other hand, when the price is high compared to the other costs, allowances are only bought when the are none emissions held and remanufacturing units most be produced.

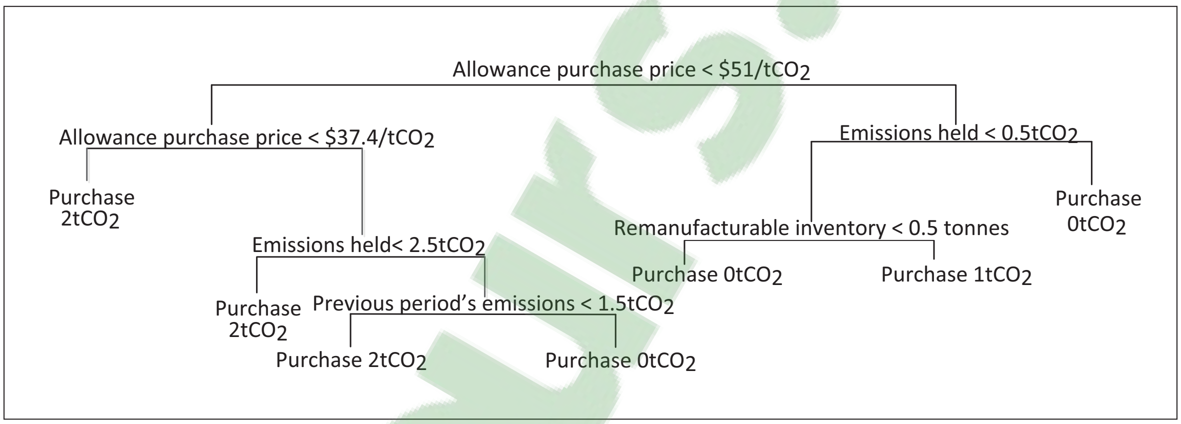


Figure 2.12 Classification tree of allowance purchase strategy in case I. Classification error= 9.59%

Figure 2.13 illustrates the allowance sale strategy. Contrary to the purchase of allowances, the allowance price, and the sale of allowances are directly correlated. When the allowance price is low, allowances are not sold. On the other hand, when the price is high, the decision to sell allowances is based on the level of emissions held and the previous period's emissions.

#### 2.5.5.2 Case II. Remanufacturing is less expensive and greener than manufacturing

Figure 2.14 shows the classification tree for the carbon purchase strategy in case II. The purchase of allowances is motivated by a low emission bank and to support the remanufacturing activities.

Figure 2.15 illustrates the allowance sale strategy in case II. As it can be seen in most of the cases, there is no sale of allowances. In fact, the sale of allowances is advised when the quantity

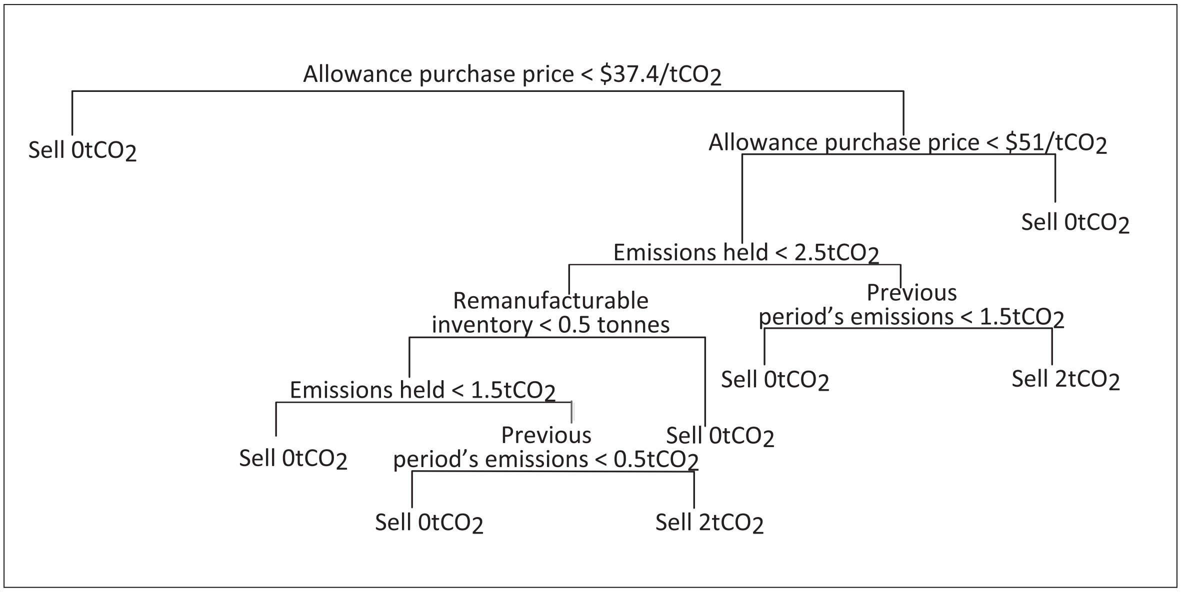


Figure 2.13 Classification tree of allowance sale strategy in case I. Classification error= 0.67%

to remanufacture is low and when the profit from the sale of allowances excesses the cost of using manufacturing.

## 2.6 Results Analysis and Managerial Insights

In this section, we analyze the impact of a cap-and-trade strategy, the emission cap and the carbon credit price fluctuations on inventory policies.

### 2.6.1 Managerial insights on the structure of inventory and carbon management policies

Results are summarized in Tables 2.5 to 2.8. Column 1 to 6 show the values of the parameters as defined for each instance. Columns 6 and 7 show respectively the inventory policy and the corresponding values defined in sections 2.5.4.1 and 2.5.4.2. The columns 8 and 9 represent respectively the optimal operating cost and the quantity of GHG emissions generated. Finally, column 10 shows the expected deviation from the optimal cost (column 8) when the policy in column 6 is applied.

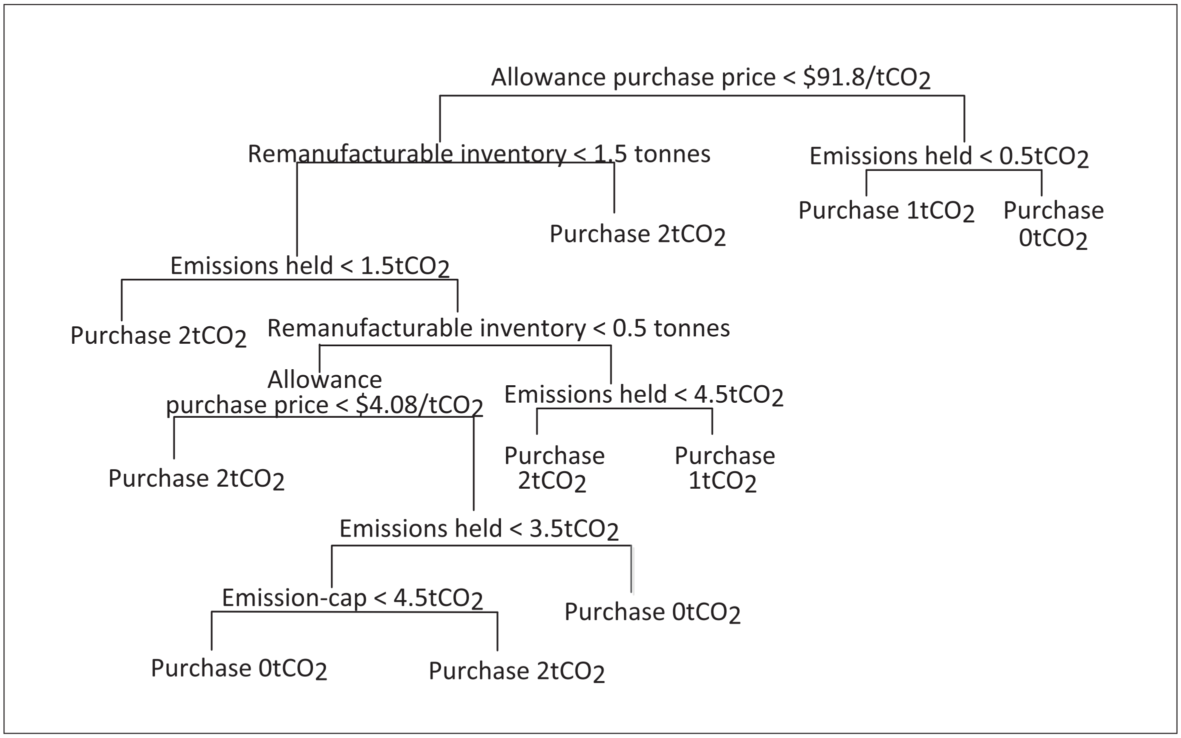


Figure 2.14 Classification tree of allowance purchase strategy in case II. Classification error= 9.78%

Table 2.5 Results from environmental scenarios with $E^c = 2$

| Scenario Parameters | | | | | | Inventory Policy Proposed | | Results | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | $C_p$ | $C_r$ | $C_c^+$ | $C_c^-$ | $E^c$ | Inventory policy | Parameters values | Optimal cost | GHG | Dev. from optimal cost(%) |
| 1 | 90 | 130 | 1.36 | 1.32 | 2 | $(S^c, \bar{q}^c)$ | (9,1) | 834.75 | 2.00 | 0.00 |
| 2 | 90 | 130 | 6.80 | 6.60 | 2 | $(S^c, \bar{q}^c)$ | (9,1) | 844.74 | 1.99 | 0.00 |
| 3 | 90 | 130 | 13.60 | 13.19 | 2 | $(S^c, \bar{q}^c)$ | (9,1) | 858.75 | 2.00 | 0.00 |
| 4 | 90 | 130 | 20.40 | 19.79 | 2 | $(S^c, \bar{q}^c)$ | (9,1) | 872.75 | 2.00 | 0.00 |
| 5 | 90 | 130 | 27.20 | 26.38 | 2 | $(S^c, \bar{q}^c)$ | (9,1) | 886.75 | 2.00 | 0.00 |
| 6 | 90 | 130 | 34.00 | 32.98 | 2 | $(S^c, \bar{q}^c)$ | (9,1) | 900.75 | 2.00 | 0.00 |
| 7 | 90 | 130 | 40.80 | 39.58 | 2 | $(S^c, \bar{q}^c)$ | (9,1) | 907.44 | 1.50 | 0.58 |
| 8 | 90 | 130 | 61.20 | 59.36 | 2 | $(\varepsilon')$ | - | 938.61 | 1.00 | 0.00 |
| 9 | 90 | 130 | 81.60 | 79.15 | 2 | $(\varepsilon')$ | - | 958.60 | 1.00 | 0.00 |
| 10 | 90 | 130 | 102.00 | 98.94 | 2 | $(\varepsilon')$ | - | 979.59 | 1.00 | 0.00 |
| 11 | 130 | 90 | 1.36 | 1.32 | 2 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,1) | 765.30 | 2.00 | 0.04 |
| 12 | 130 | 90 | 6.80 | 6.60 | 2 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 774.56 | 1.92 | 0.04 |
| 13 | 130 | 90 | 13.60 | 13.19 | 2 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 788.65 | 1.90 | 0.02 |
| 14 | 130 | 90 | 20.40 | 19.79 | 2 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 802.32 | 1.92 | 0.17 |
| 15 | 130 | 90 | 27.20 | 26.38 | 2 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 815.64 | 1.87 | 0.01 |
| 16 | 130 | 90 | 34.00 | 32.98 | 2 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 828.71 | 1.87 | 0.01 |
| 17 | 130 | 90 | 40.80 | 39.58 | 2 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 838.92 | 1.88 | 0.04 |
| 18 | 130 | 90 | 61.20 | 59.36 | 2 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 878.61 | 1.84 | 0.08 |
| 19 | 130 | 90 | 81.60 | 79.15 | 2 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 914.71 | 1.73 | 0.27 |
| 20 | 130 | 90 | 102.00 | 98.94 | 2 | $(\varepsilon')$ | - | 939.61 | 1.00 | 0.00 |

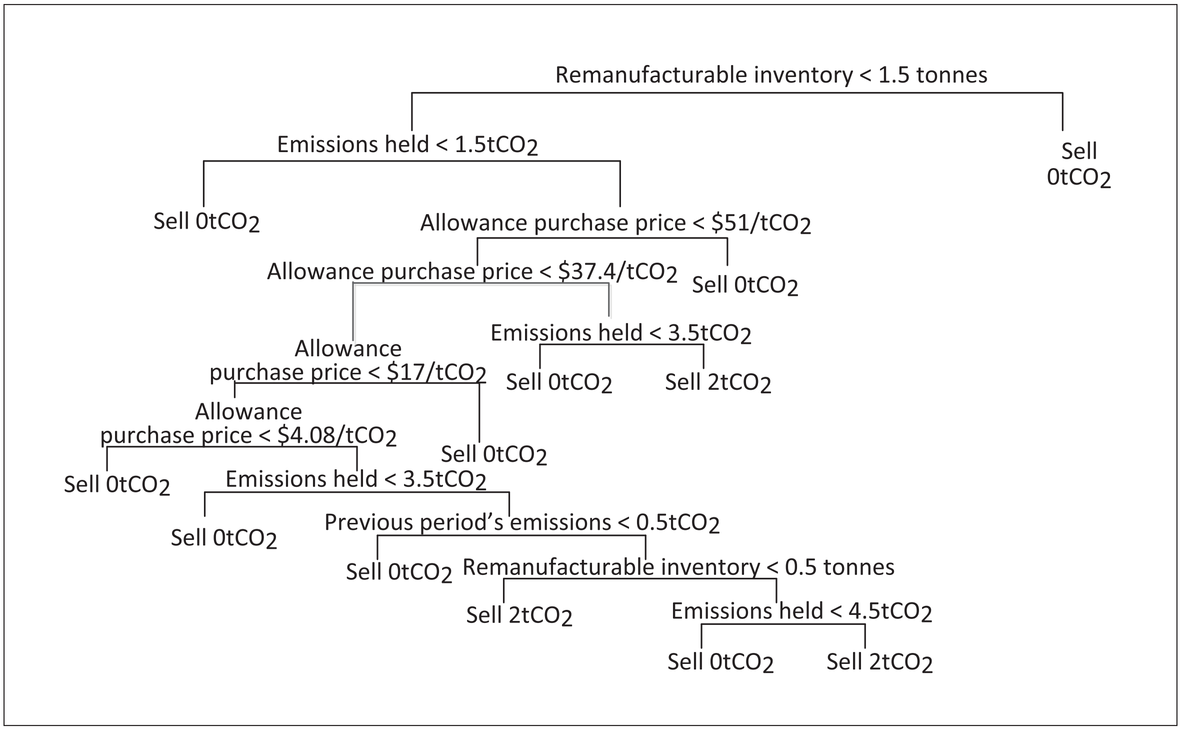


Figure 2.15 Classification tree of allowance sale strategy in case II. Classification error= 1.46%

Table 2.6 Results from environmental scenarios with $E^c = 3$

| Scenario Parameters | | | | | | Inventory Policy Proposed | | Results | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | $C_p$ | $C_r$ | $C_c^+$ | $C_c^-$ | $E^c$ | Inventory policy | Parameters values | Optimal cost | GHG | Dev. from optimal cost(%) |
| 1 | 90 | 130 | 1.36 | 1.32 | 3 | $(S^c, \bar{q}^c)$ | (9,1) | 834.22 | 2.00 | 0.04 |
| 2 | 90 | 130 | 6.80 | 6.60 | 3 | $(S^c, \bar{q}^c)$ | (9,1) | 844.19 | 1.97 | 0.04 |
| 3 | 90 | 130 | 13.60 | 13.19 | 3 | $(S^c, \bar{q}^c)$ | (9,1) | 858.22 | 2.00 | 0.04 |
| 4 | 90 | 130 | 20.40 | 19.79 | 3 | $(S^c, \bar{q}^c)$ | (9,1) | 872.22 | 2.00 | 0.04 |
| 5 | 90 | 130 | 27.20 | 26.38 | 3 | $(S^c, \bar{q}^c)$ | (9,1) | 886.22 | 2.00 | 0.04 |
| 6 | 90 | 130 | 34.00 | 32.98 | 3 | $(S^c, \bar{q}^c)$ | (9,1) | 900.22 | 2.00 | 0.04 |
| 7 | 90 | 130 | 40.80 | 39.58 | 3 | $(\varepsilon')$ | - | 901.51 | 1.60 | 1.23 |
| 8 | 90 | 130 | 61.20 | 59.36 | 3 | $(\varepsilon')$ | - | 938.61 | 1.00 | 0.00 |
| 9 | 90 | 130 | 81.60 | 79.15 | 3 | $(\varepsilon')$ | - | 958.60 | 1.00 | 0.00 |
| 10 | 90 | 130 | 102.00 | 98.94 | 3 | $(\varepsilon')$ | - | 979.59 | 1.00 | 0.00 |
| 11 | 130 | 90 | 1.36 | 1.32 | 3 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,1) | 763.38 | 2.00 | 0.06 |
| 12 | 130 | 90 | 6.80 | 6.60 | 3 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 772.37 | 1.92 | 0.03 |
| 13 | 130 | 90 | 13.60 | 13.19 | 3 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 786.87 | 1.92 | 0.04 |
| 14 | 130 | 90 | 20.40 | 19.79 | 3 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 800.70 | 1.93 | 0.15 |
| 15 | 130 | 90 | 27.20 | 26.38 | 3 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 814.09 | 1.88 | 0.01 |
| 16 | 130 | 90 | 34.00 | 32.98 | 3 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 827.24 | 1.88 | 0.02 |
| 17 | 130 | 90 | 40.80 | 39.58 | 3 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 837.29 | 1.90 | 0.07 |
| 18 | 130 | 90 | 61.20 | 59.36 | 3 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 877.68 | 1.86 | 0.09 |
| 19 | 130 | 90 | 81.60 | 79.15 | 3 | $(s^d, S^d, r^d, \bar{q}^d)$ | (4,9,2,0) | 914.38 | 1.78 | 0.09 |
| 20 | 130 | 90 | 102.00 | 98.94 | 3 | $(\varepsilon')$ | - | 939.61 | 1.00 | 0.00 |

Table 2.7  Results from environmental scenarios with $E^c = 4$

| Scenario Parameters | | | | | | Inventory Policy Proposed | | Results | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | $C_p$ | $C_r$ | $C_c^+$ | $C_c^-$ | $E^c$ | Inventory policy | Parameters values | Optimal cost | GHG | Dev. from optimal cost (%) |
| 1 | 90 | 130 | 1.36 | 1.32 | 4 | $(S^c,\bar{q}^c)$ | (9,1) | 833.46 | 2.00 | 0.01 |
| 2 | 90 | 130 | 6.80 | 6.60 | 4 | $(S^c,\bar{q}^c)$ | (9,1) | 843.45 | 1.98 | 0.01 |
| 3 | 90 | 130 | 13.60 | 13.19 | 4 | $(S^c,\bar{q}^c)$ | (9,1) | 857.56 | 2.00 | 0.01 |
| 4 | 90 | 130 | 20.40 | 19.79 | 4 | $(S^c,\bar{q}^c)$ | (9,1) | 871.46 | 2.00 | 0.01 |
| 5 | 90 | 130 | 27.20 | 26.38 | 4 | $(S^c,\bar{q}^c)$ | (9,1) | 885.46 | 2.00 | 0.00 |
| 6 | 90 | 130 | 34.00 | 32.98 | 4 | $(S^c,\bar{q}^c)$ | (9,1) | 899.46 | 2.00 | 0.00 |
| 7 | 90 | 130 | 40.80 | 39.58 | 4 | $(S^c,\bar{q}^c)$ | (9,1) | 901.46 | 1.60 | 1.11 |
| 8 | 90 | 130 | 61.20 | 59.36 | 4 | $(\varepsilon')$ | - | 938.61 | 1.00 | 0.00 |
| 9 | 90 | 130 | 81.60 | 79.15 | 4 | $(\varepsilon')$ | - | 958.60 | 1.00 | 0.00 |
| 10 | 90 | 130 | 102.00 | 98.94 | 4 | $(\varepsilon')$ | - | 979.59 | 1.00 | 0.00 |
| 11 | 130 | 90 | 1.36 | 1.32 | 4 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,1) | 761.99 | 2.00 | 0.07 |
| 12 | 130 | 90 | 6.80 | 6.60 | 4 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 770.93 | 1.93 | 0.05 |
| 13 | 130 | 90 | 13.60 | 13.19 | 4 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 785.51 | 1.93 | 0.04 |
| 14 | 130 | 90 | 20.40 | 19.79 | 4 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 799.47 | 1.94 | 0.14 |
| 15 | 130 | 90 | 27.20 | 26.38 | 4 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 812.93 | 1.89 | 0.02 |
| 16 | 130 | 90 | 34.00 | 32.98 | 4 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 826.17 | 1.89 | 0.03 |
| 17 | 130 | 90 | 40.80 | 39.58 | 4 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 836.28 | 1.91 | 0.08 |
| 18 | 130 | 90 | 61.20 | 59.36 | 4 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 877.04 | 1.88 | 0.09 |
| 19 | 130 | 90 | 81.60 | 79.15 | 4 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 914.11 | 1.82 | 0.11 |
| 20 | 130 | 90 | 102.00 | 98.94 | 4 | $(\varepsilon')$ | - | 939.61 | 1.00 | 0.00 |

Table 2.8  Results from environmental scenarios with $E^c = 5$

| Scenario Parameters | | | | | | Inventory Policy Proposed | | Results | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | $C_p$ | $C_r$ | $C_c^+$ | $C_c^-$ | $E^c$ | Inventory policy | Parameters values | Optimal cost | GHG | Dev. from optimal cost(%) |
| 1 | 90 | 130 | 1.36 | 1.32 | 5 | $(S^c,\bar{q}^c)$ | (9,1) | 833.11 | 2.00 | 0.02 |
| 2 | 90 | 130 | 6.80 | 6.60 | 5 | $(S^c,\bar{q}^c)$ | (9,1) | 843.10 | 1.99 | 0.02 |
| 3 | 90 | 130 | 13.60 | 13.19 | 5 | $(S^c,\bar{q}^c)$ | (9,1) | 857.11 | 2.00 | 0.02 |
| 4 | 90 | 130 | 20.40 | 19.79 | 5 | $(S^c,\bar{q}^c)$ | (9,1) | 871.11 | 2.00 | 0.02 |
| 5 | 90 | 130 | 27.20 | 26.38 | 5 | $(S^c,\bar{q}^c)$ | (9,1) | 885.11 | 2.00 | 0.02 |
| 6 | 90 | 130 | 34.00 | 32.98 | 5 | $(S^c,\bar{q}^c)$ | (9,1) | 899.11 | 2.00 | 0.02 |
| 7 | 90 | 130 | 40.80 | 39.58 | 5 | $(\varepsilon')$ | - | 901.42 | 1.60 | 1.09 |
| 8 | 90 | 130 | 61.20 | 59.36 | 5 | $(\varepsilon')$ | - | 938.61 | 1.00 | 0.00 |
| 9 | 90 | 130 | 81.60 | 79.15 | 5 | $(\varepsilon')$ | - | 958.60 | 1.00 | 0.00 |
| 10 | 90 | 130 | 102.00 | 98.94 | 5 | $(\varepsilon')$ | - | 979.59 | 1.00 | 0.00 |
| 11 | 130 | 90 | 1.36 | 1.32 | 5 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,1) | 760.93 | 2.00 | 0.08 |
| 12 | 130 | 90 | 6.80 | 6.60 | 5 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 769.85 | 1.94 | 0.06 |
| 13 | 130 | 90 | 13.60 | 13.19 | 5 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 784.40 | 1.94 | 0.04 |
| 14 | 130 | 90 | 20.40 | 19.79 | 5 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 798.55 | 1.95 | 0.14 |
| 15 | 130 | 90 | 27.20 | 26.38 | 5 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 812.05 | 1.90 | 0.03 |
| 16 | 130 | 90 | 34.00 | 32.98 | 5 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 825.36 | 1.90 | 0.04 |
| 17 | 130 | 90 | 40.80 | 39.58 | 5 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 835.56 | 1.93 | 0.08 |
| 18 | 130 | 90 | 61.20 | 59.36 | 5 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 876.60 | 1.90 | 0.08 |
| 19 | 130 | 90 | 81.60 | 79.15 | 5 | $(s^d,S^d,r^d,\bar{q}^d)$ | (4,9,2,0) | 913.96 | 1.83 | 0.19 |
| 20 | 130 | 90 | 102.00 | 98.94 | 5 | $(\varepsilon')$ | - | 939.61 | 1.00 | 0.00 |

In the following paragraphs, we compare inventory policies characterized in the context of the baseline and environmental scenarios using cases I and II.

#### 2.6.1.1 Case I. Remanufacturing is more expensive, but greener than manufacturing

The green and the baseline scenario in case I can be described by a restricted base stock policy where there is a maximal production quantity. However, it is important to notice that because in the environmental scenario the carbon footprint is a constraint, remanufacturing which is the greener process is used, contrary to the baseline case. As a result, the decisions are not as simple as in the baseline case.

#### 2.6.1.2 Case II. Remanufacturing is less expensive and greener than manufacturing

For case II, we would have expected the same inventory policies in the baseline and the green scenario. Only differing by the fact that the replenishment orders would be capped by the emission bank.

Manufacturing in case II is used only to decrease the emission bank since it is the more expensive process, unlike under the same inventory policy in case I.

### 2.6.2 Impact of Carbon Prices on Inventory Policies

In general, the carbon price explains most of the changes observed when we introduced the cap-and-trade scheme.

#### 2.6.2.1 Case I. Remanufacturing is more expensive, but greener than manufacturing

In case I, even though manufacturing is supposed to be the less expensive process, it predominates only when the carbon credit price is below \$40/t$CO_2$. If the environmental impact of each process is considered, remanufacturing is cheaper than manufacturing at \$40/t$CO_2$. Moreover, when the carbon price is higher than \$44.50/t$CO_2$, the manufacturing cost exceeds the cost of lost sales. When the carbon price is increased up to \$50t$CO_2$, the cost of remanufacturing likewise exceeds the cost of losing a sale. In this case, the system is not profitable, the only constraint satisfied is the minimal recovery, and most of the demand is lost. This situation explains why both the $(S^c, \bar{q}^c)$ and $\varepsilon'$ policies exist and why the former (which uses manufacturing and remanufacturing) is applicable when the carbon price is below \$40/t$CO_2$ and the latter when this price is reached.

We define the threshold carbon price as the price beyond which stopping manufacturing and/or remanufacturing is preferred over investing in carbon credits. Below this price, an inventory policy is effective in balancing the environmental impact against costs; above it, system profitability does not increase. In case I, this price is \$44.50/t$CO_2$.

The existence of the threshold price affects all decisions and the state of the system. While manufacturing is ongoing, the serviceable inventory (Figure 2.16) is full most of the time, then assuring a high service level (Figure 2.17). However, during periods in which demand is met through remanufacturing alone, the number of lost sales increases significantly, because of the uncertainty and low level of product returns. Furthermore, when remanufacturing is stopped completely, the serviceable inventory is emptied, and lost sales increase further, while remanufacturable inventory (which generally remains low) increases (Figure 2.18). In this situation, it would be advisable to make strategic decisions such as low-carbon technology investments.

#### 2.6.2.2 Case II. Remanufacturing is less expensive and greener than manufacturing

We can also extend this analysis to the case when remanufacturing is the most cost-efficient activity. The threshold carbon price in case II is \$24.5/t$CO_2$. Manufacturing is stopped when the allowance price reaches \$24.5/t$CO_2$, and remanufacturing stops when the prices exceeded \$89/t$CO_2$.

Contrary to case I, in case II remanufacturing is stopped at a higher allowance price. Then, we observed a higher serviceable inventory (Figure 2.19) and service level (Figure 2.20 for a longer interval of allowance prices.

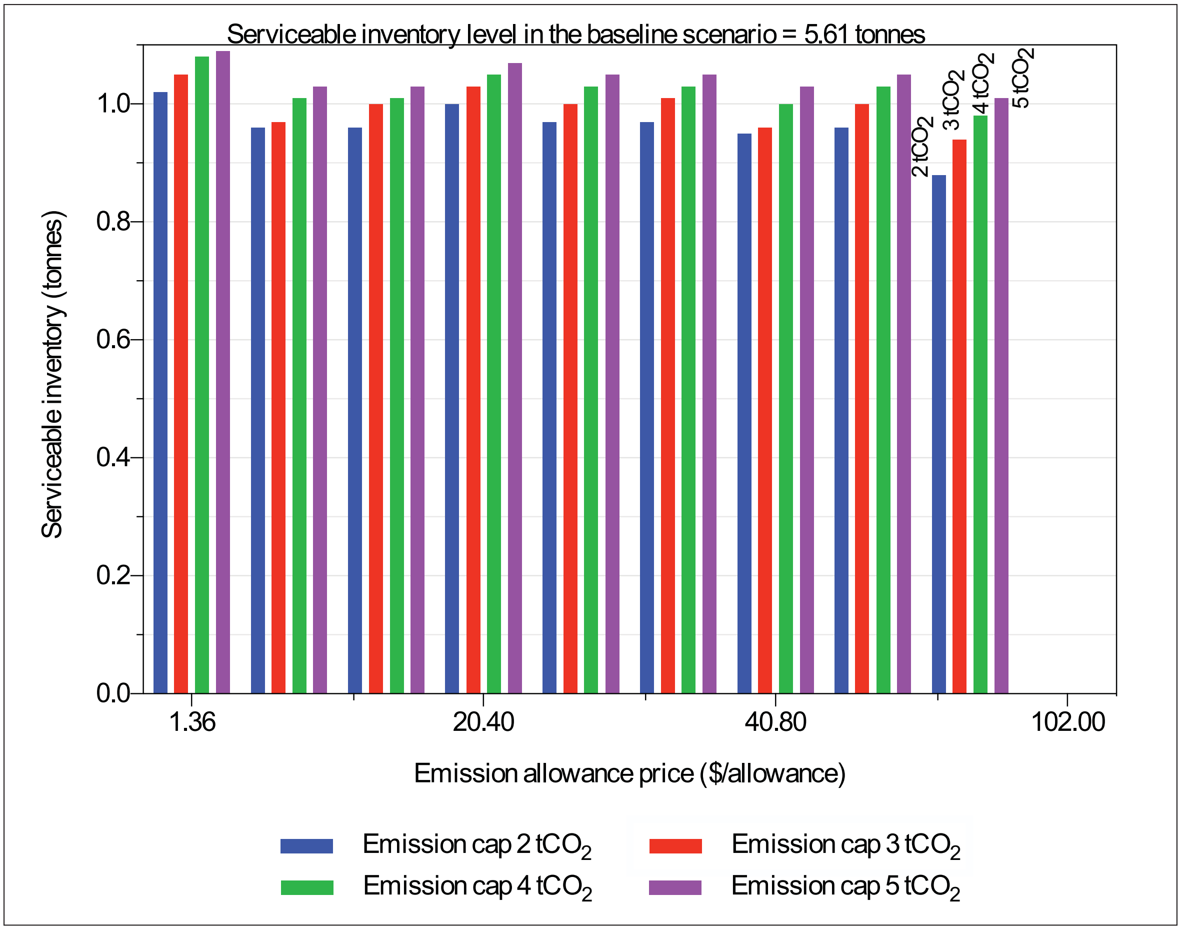


Figure 2.16 Expected serviceable inventory per scenario case I

In case II remanufacturing is exploited to its maximum capacity. Thus, the remanufacturable inventory level is much lower than that of case I.

### 2.6.3 Impact of the emission cap on decisions

Based on our results, there is insufficient proof that the emission cap has an impact on emission quantities and the cost of the system. It seems to exist a weak correlation between the decisions and the emission cap. Nevertheless, the cap might have an effect on the replenishment decisions, but this question needs to be studied in greater depth.

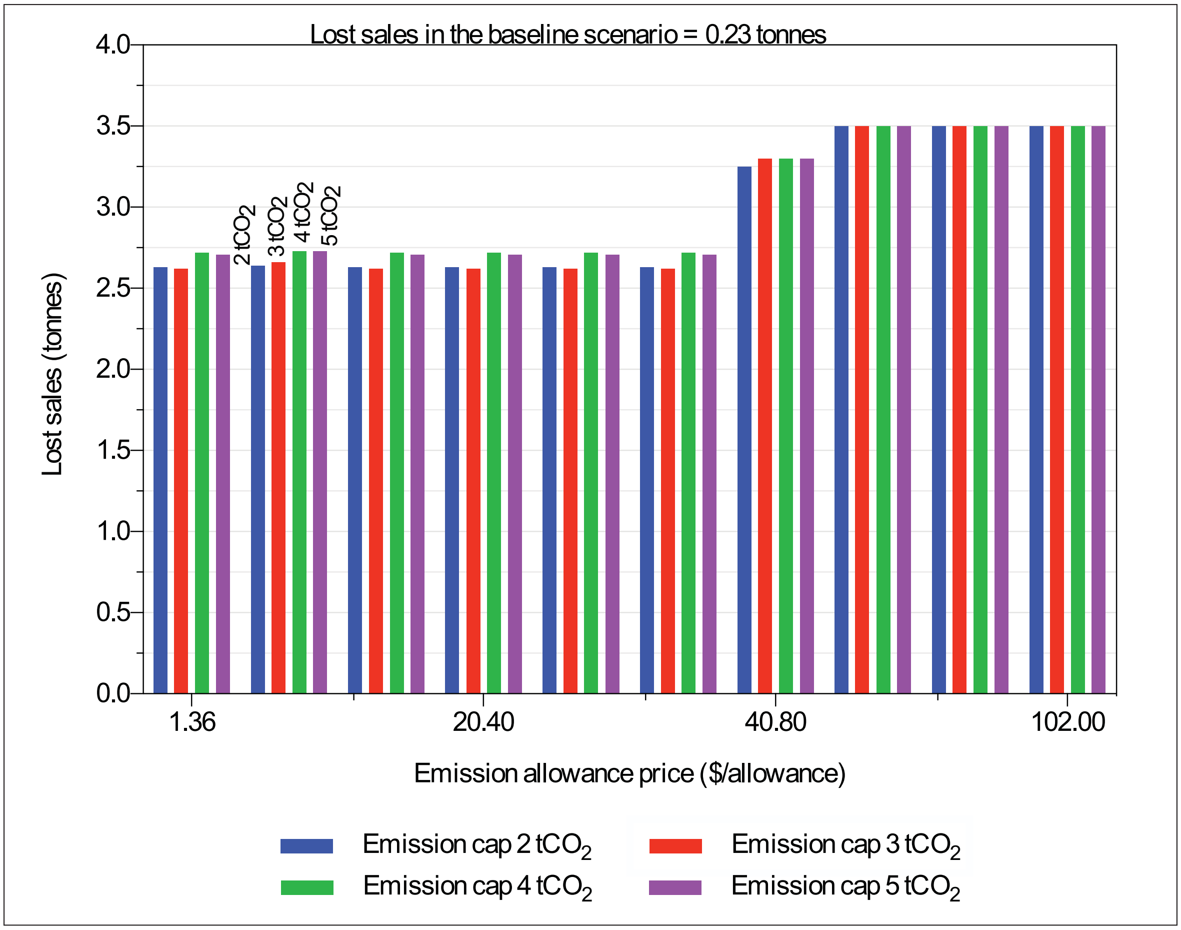


Figure 2.17 Expected lost sales per scenario case I

#### 2.6.3.1 Managerial Insights regarding the effect of a cap-and-trade

We may summarize the findings as follows. Environmental constraints should direct inventory policy structure. In general, in the environmental scenario, replenishment decisions need to track additional states such as the emission bank, and in some instances they depend on additional inventory parameters. Furthermore, the integration of manufacturing and remanufacturing appears highly dependent on their environmental and financial impact.

In terms of the gain in environmental performance achieved by restructuring decision-making. The results show that inventory control helps to reduce the environmental impact of the company in terms of the amount of emissions. In case I (Figure 2.22), a reduction of 5.64t$CO_2$

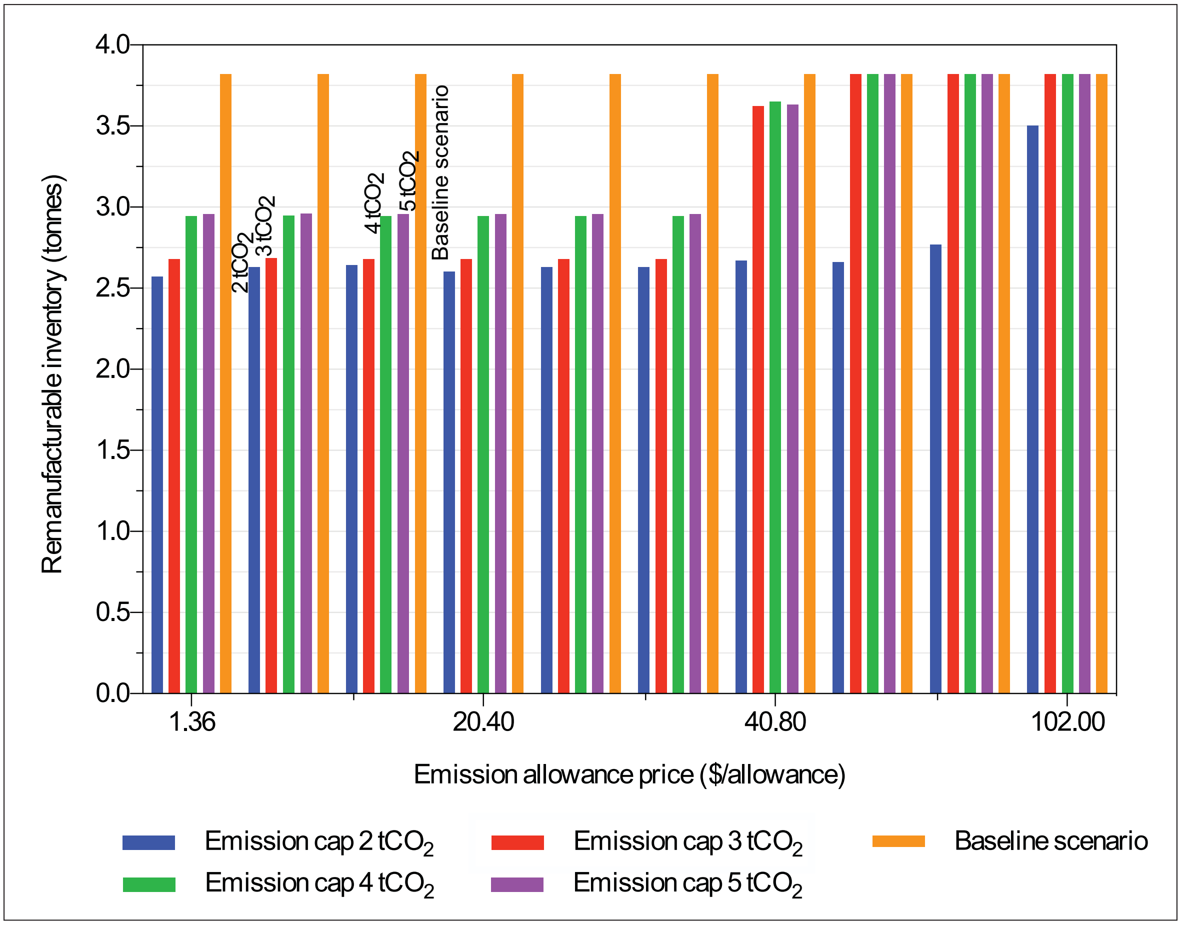


Figure 2.18 Expected remanufacturable inventory per scenario case I

was achieved in all instances. In case II (Figure 2.23), the reduction averaged 4.73t$CO_2$ with a standard deviation of 0.03. On the other hand, we note that emissions were 2t$CO_2$ in case I and 1.92t$CO_2$ in case II with a standard deviation of 0.03. These levels are close to the purchase allowance limit in all scenarios, suggesting that the emission cap is too severe, in view of the environmental impact of both production activities. A broader range of instances should be studied in order to determine the actual impact of the emission cap. However, this would run into a problem associated the solution methods, since resolution time is tied to the state and action space. The results nevertheless show that inventory control is an effective approach to reducing the amount of emissions and ensuring compliance with environmental laws without jeopardizing the future of the company.

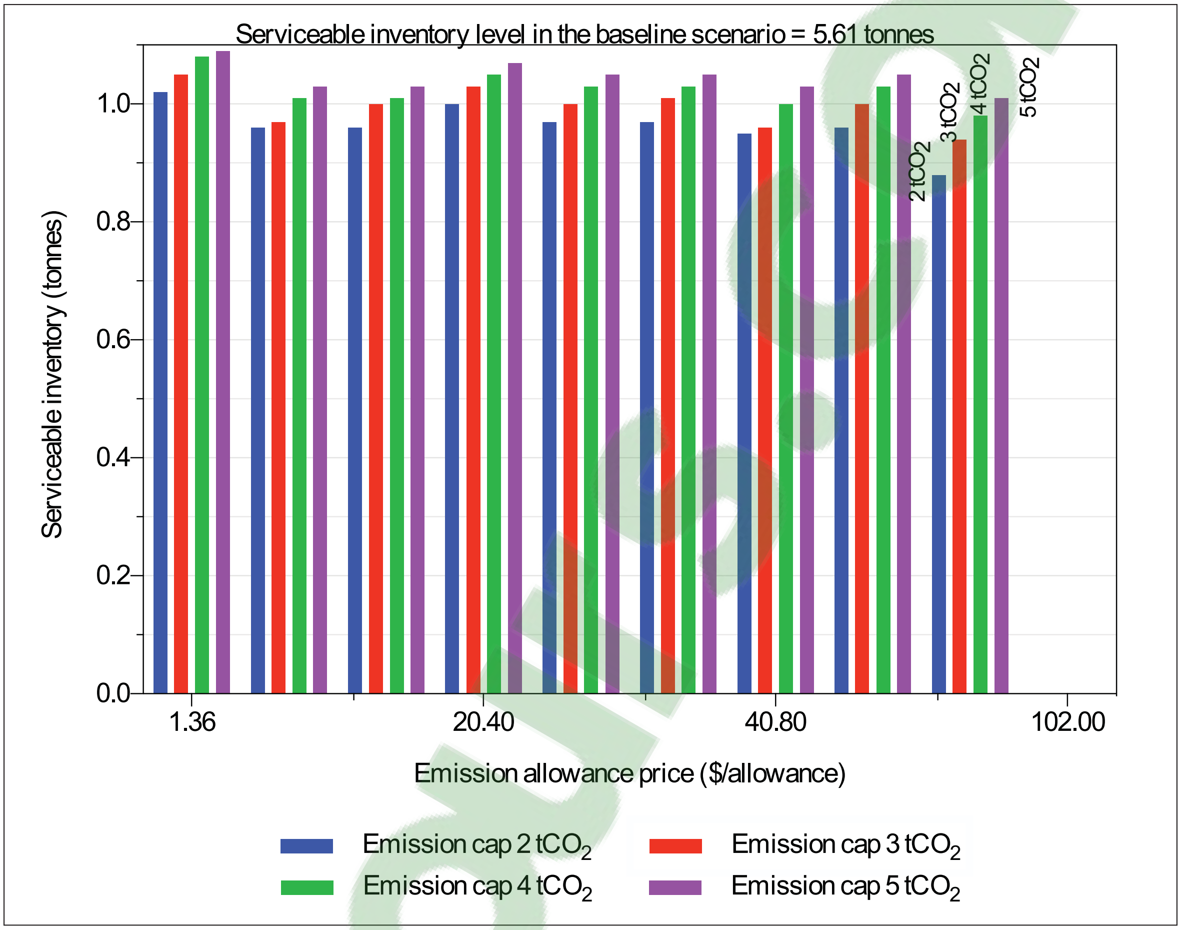


Figure 2.19 Expected serviceable inventory in case II

In conclusion, the results obtained here imply that the suitability of inventory policies changes depending on constraints associated with environmental legislation. We can see that inventory control provides the company with some flexibility, but as the carbon allowance price increases, the impact of the inventory decisions decreases. Underlying factors such as the emission cap and the emission price clearly have an impact on the effectiveness of the inventory policy. We can say that there is in general an emission price threshold value beyond which inventory control no longer helps the company operate within the environmental constraint without sacrificing the service level. Stopping a sourcing process because continuing to use it is more expensive than losing a sale does not make the company more profitable, and therefore does not make economic sense. In this scenario, it would be preferable to explore strategic decisions such as investing in greener technology. For as long as the most enviro-friendly process is also

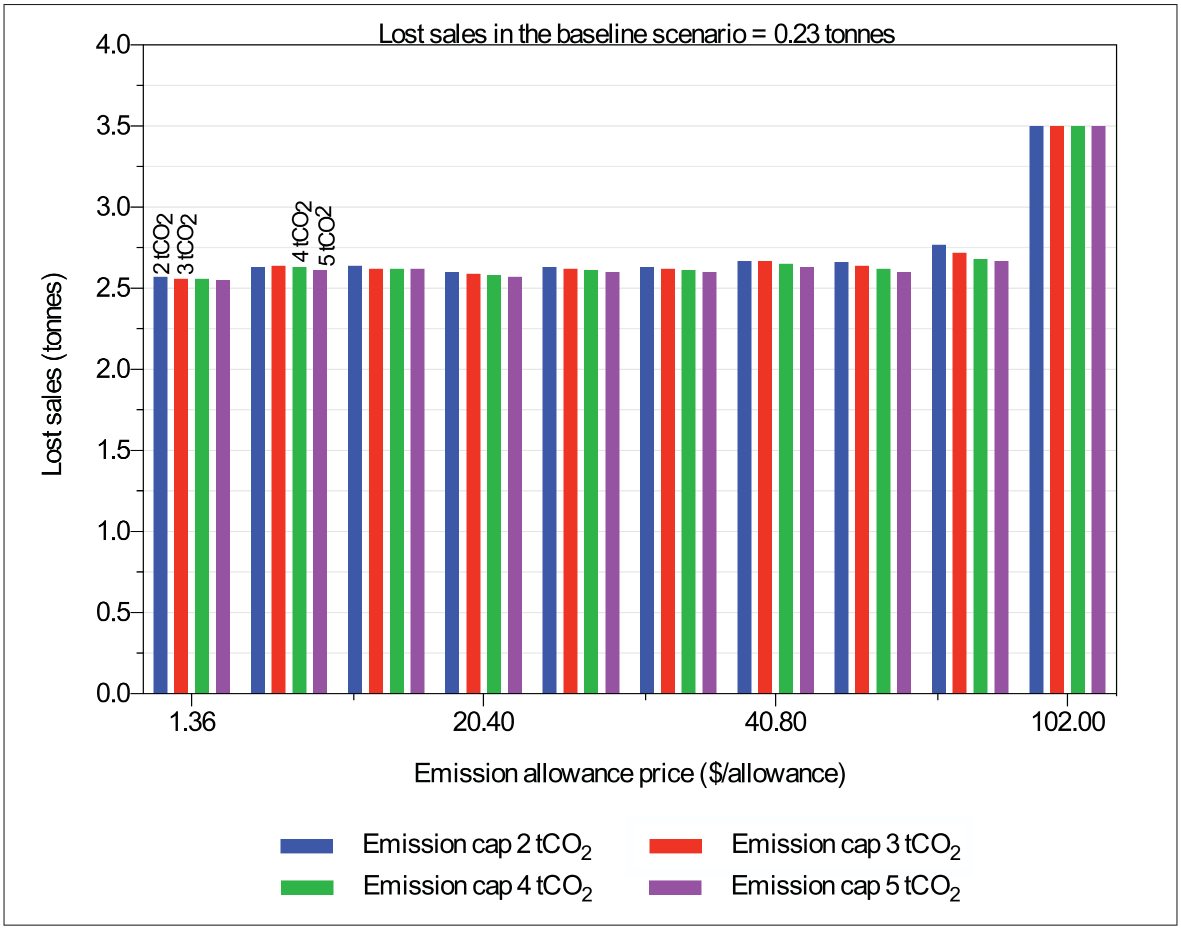


Figure 2.20 Expected lost sales per scenario in case II

the most expensive, it is ultimately advisable to change the inventory policy in order to take advantage of selling emissions.

## 2.7 Conclusions

In this paper, we present the first study of the role and the impacts of inventory decisions on systems operating under remanufacturing and carbon emission constraints. We proposed a new methodology to characterize joint product recovery and carbon management under a cap-and-trade scheme. The major finding in this study is the demonstration that inventory policies must be adjusted to be in compliance with environmental regulation without significant cost increase.

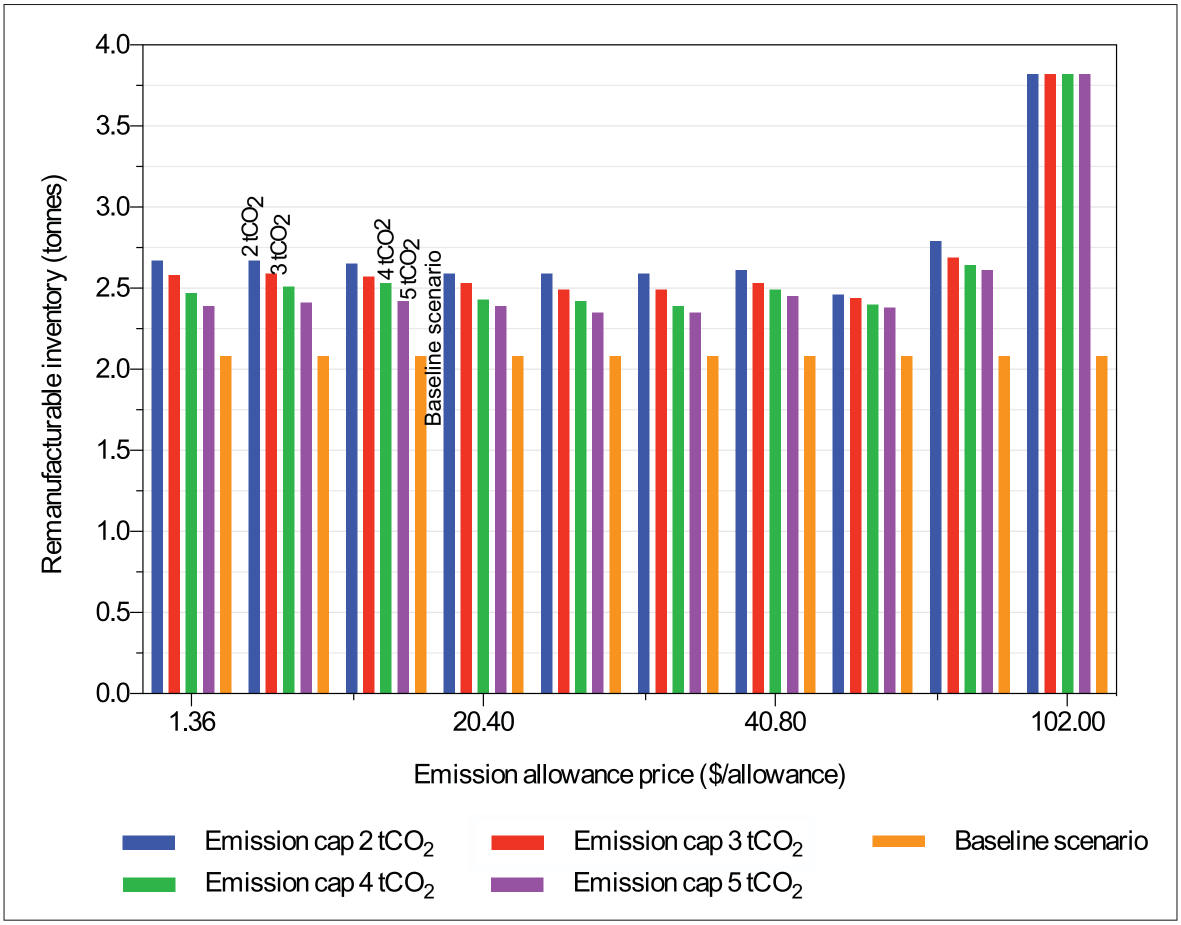


Figure 2.21 Expected remanufacturable inventory per scenario case II

The findings present insights into the role of inventory control in ensuring the environmental performance of an industrial company. The results suggest that restructuring inventory policies is helpful in the quest to reduce carbon emissions. Carbon credit prices in particular affect inventory decisions. Moreover, there is a critical carbon price beyond which the company must focus on strategic decisions such as technology investment instead of tactical operating decisions, since measures such as inventory control alone might not be sufficient to meet environmental standards. The structure of the modified inventory policy depends on several parameters and conditions. However, there is nothing preventing their integration into current management systems. The possibility of integrating carbon management systems that provide accurate information about the true environmental status of the company needs to be hi-lighted, in particular carbon management strategies and inventory control policies in the same resource

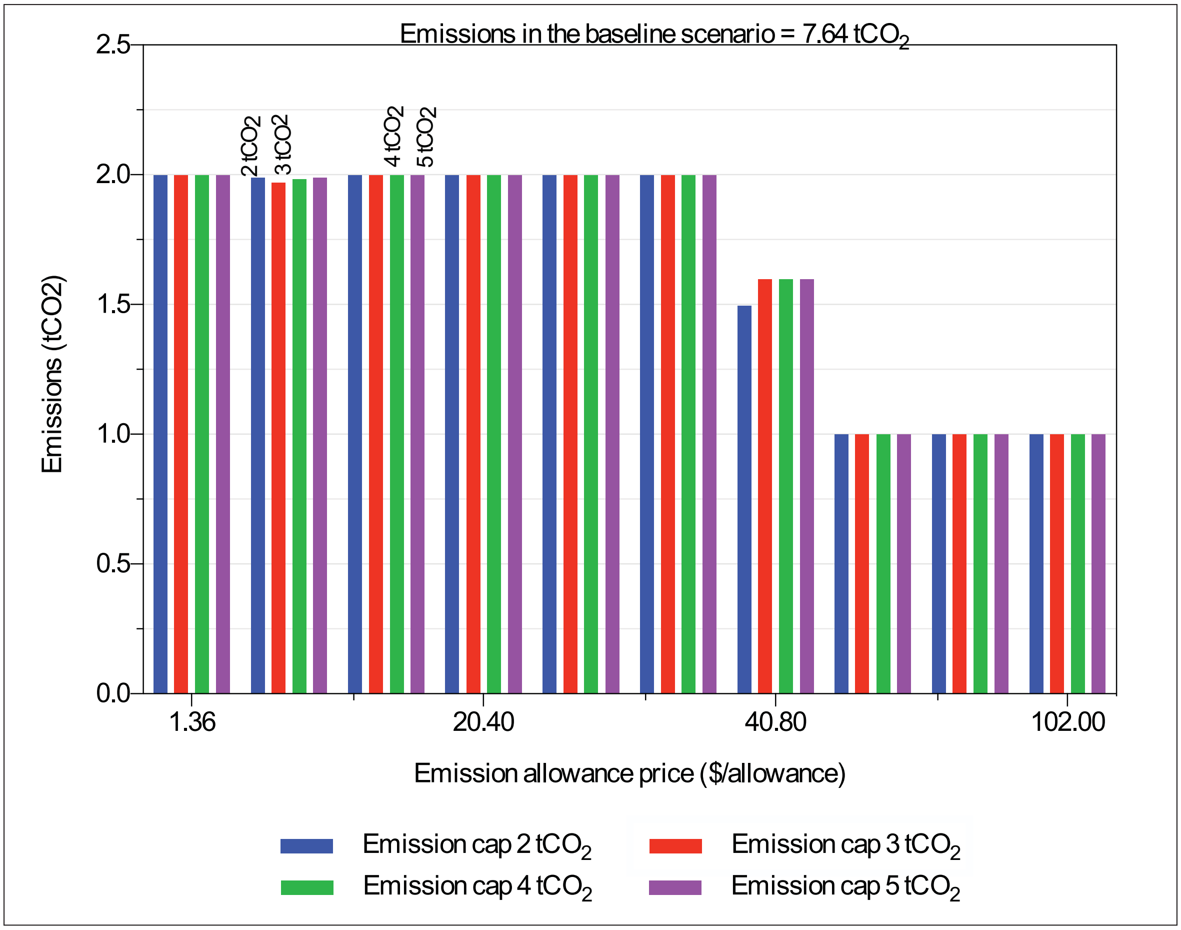


Figure 2.22 Expected emissions ($tCO_2$) per scenario case I

planning system. This is crucial for companies that have to include their environmental liabilities in their financial statements.

Finally, this study provides a clear justification why companies should consider inventory control as a complementary approach to cost control and GHG reduction. The research question was formulated as a minimization problem since we sought to analyze the impact of environmental constraints on cost. Our results appear to indicate that green inventory policies represent a promising area for further research. This paper provides a first step towards better understanding of how inventory policies react in the presence of the two important environmental regulations: product reuse and GHG reduction. Several directions could be considered for extending this research. For further managerial insights, it would be interesting to study a

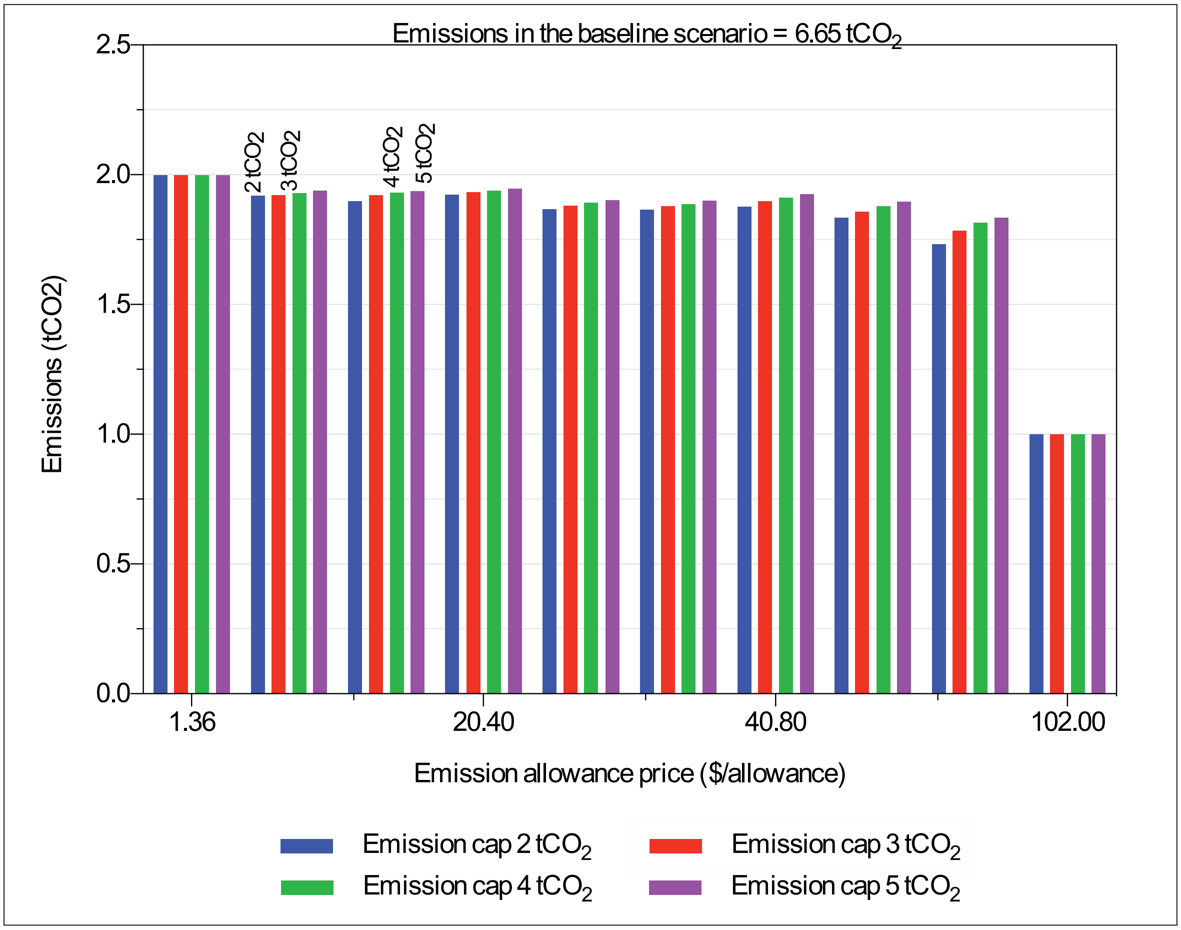


Figure 2.23 Expected emissions ($tCO_2$) per scenario case II

system based on a revenue maximization approach in which sales distribution varies according to the environmental activism of companies. This could suggest means of improving profitability, which would stimulate the involvement of management in a wide range of industries, even without environmental legislation. The model presented here should remain applicable with suitable changes to the objective function. Another possible direction would be to study other supply chain structures such as an assembly system typifying the automotive sector, an industry subject to both remanufacturing and carbon-reduction legislation.

# CHAPTER 3

## ON INVENTORY CONTROL OF PRODUCT RECOVERY SYSTEMS SUBJECT TO ENVIRONMENTAL MECHANISMS

Marthy García Alvarado[1], Marc Paquet[1], Amin Chaabane[1]

[1] Department of automated manufacturing engineering, École de technologie supérieure,

1100 Notre-Dame Ouest, Montreal, Quebec, Canada H3C 1K3

Paper published in International Journal of Production Economics.

### Abstract

The aim of this paper is to study the impact of inventory control in reducing the carbon footprint of an organization. Through a stochastic inventory model, our research extends the traditional minimization cost problem by incorporating environmental legislation. We consider a finite-horizon closed-loop system whereby decisions are subject to an emissions trading scheme and to random demand and returns. Demand can be satisfied by two sources. The primary source is environmentally friendly but expensive, whereas the second is cost effective but with negative environmental consequences. The problem is formulated as a stochastic dynamic problem, where replenishment and carbon management decisions must be made at each period. The objective is to describe how replenishment and carbon management strategies are affected by environmental constraints. In particular, considering the computation restriction of dynamic programming, in order to extend the results, we propose a genetic algorithm to find near-optimal solutions for larger instances. A sensitivity analysis is performed to identify the impact of carbon allowance prices, emission-cap and other environmental factors in the decision-making process. The results indicate that environmental strategies and their factors have an impact on replenishment decisions. There is an emission-cap from which a company must focus on strategic decisions rather than on tactical and operational decisions. In addition, if the carbon allowance price is such that the environmental benefit absorbs the cost of less polluting technology, a change in the inventory policy must be made.

**Keywords:** Inventory control, cap-and-trade systems, closed-loop system, genetic algorithms

## 3.1 Introduction

In view of environmental legislation and the increasing costs of resources, environmental performance has become a major concern for many companies. In such context, production, transportation and sourcing decisions play a key role in reducing an organization's negative environmental impact (Benjaafar et al., 2013). Therefore, decision-making models should be improved in order to develop appropriate planning methods which balance environmental performance against costs. There exists a range of possibilities for a model integrating environmental concerns and logistics. End-of-life product recovery and greenhouse-gas (GHG) reduction are two main approaches studied by researchers.

Motivations for product recovery include reduction of waste, minimization of raw material, and reduction of life cycle cost, among others. Caterpillar is an example of a pioneer company in product recovery; it has already made a business priority the practice of returning end-of-life products to like-new conditions. Meanwhile, GHG reduction is mainly motivated by altruism, climate programs, and economic benefits (Veen and Venugopal, 2014). Examples of these programs include the European Union Emissions Trading Scheme (EU ETS), the Western Climate Initiative (WCI) and the Regional Greenhouse Gas Initiative (RGGI). Those initiatives seek to reduce GHG emissions by implementing a cap-and-trade mechanism, where the industries must respect an emission-quota and may trade carbon allowances. Multiple countries as the United States, Canada and those in the European Union are implementing these programs.

Several authors have studied inventory control of product recovery systems. In van der Laan et al. (2004), the optimal inventory policy for a hybrid manufacturing/remanufacturing system is derived. Later in Ahiska and King (2010), setup costs were included. In parallel, GHG reduction policies such as 1) emission-tax, 2) direct-cap, and 3) cap-and-trade have also been the subject of various studies. The Economic Order Quantity (EOQ) has been reformulated in Bouchery et al. (2012) to include the sustainable objectives. The authors in Liu et al. (2013)

compute the optimal order quantity for retailers when a cap-and-trade mechanism is considered. For their part, in Toptal et al. (2014) is presented an extension of the EOQ model to include alternative environmental policies. Ultimately, in García-Alvarado et al. (2014) have been shown that the inventory policy is affected when emissions are considered in an infinite-horizon closed-loop system.

As each year, the emission-cap and environmental legislation are adjusted according to the sector and the environmental standards of the year, a finite-horizon approach may be more appropriate to simulate the dynamics of the environmental legislation. Although numerous researchers have studied recovery systems, to our knowledge, no author has studied a finite-horizon recovery system subject to environmental constraints. This raises the question whether environmental policies affect replenishment and carbon management strategies in a finite-horizon product recovery system. Thus, the aim of the paper is threefold: 1) to present a stochastic inventory model incorporating environmental constraints, 2) to present a solution method to overcome the solution difficulties, and 3) to provide a set of managerial insights on the knowledge of joint inventory control and carbon footprint reduction. The rest of this paper is organized as follows: the following section surveys the recently emerged research on product recovery and environmental inventory systems. Section 3.3 presents the inventory model. Section 3.4 introduce a dynamic programming solution approach. Section 3.5 presents a genetic algorithm for extending our results. Numerical results are carried out in Section 3.6. Section 3.7 summarizes the results and suggests some directions for future research.

## 3.2 Literature review

Throughout this work, we are interested in two streams: 1) inventory control of product recovery systems and 2) inventory control subject to environmental constraints.

The authors in Simpson (1978); Inderfurth (1997) conducted initial research of recovery systems. They characterized the optimal inventory policy for a product recovery system with single-period lead-times and random demand and returns. The inventory policy is characterized by three parameters: 1) the manufacturing-up-to-level ($S_{p,t}$), 2) the remanufacturing-up-to-level ($S_{r,t}$) and 3) the disposal-down-to-level ($U_t$). Each parameter denotes the trigger to produce, remanufacture, and dispose, respectively. The authors in van der Laan et al. (2004), extended the model presented by Inderfurth (1997). A hybrid system ($S_p$, $S_r$, $U$) under finite-horizon with different lead-times, demand, and returns were introduced. In Bayındır et al. (2006) the authors explored a recovery system under alternative inventory control policies. They determined the desired level of recovery given a probability of failure at the recovery operation. Recent literature such as Ahiska and King (2010) extended the model in Inderfurth (1997). The authors considered setup costs and different lead-time structures over an infinite-horizon. Modeling the system as a discrete-time Markovian Decision Process (MDP), the authors were able to characterize the optimal policy. Hence, for the given scenario, the optimal policy comprises four parameters: 1) the reorder level for manufacturing ($s_p$), 2) the manufacturing-up-to-level ($S_p$), 3) the reorder level for remanufacturing ($s_r$) and 4) the minimal quantity to remanufacture ($q_r$). Later on, the study in Naeem et al. (2013) studied the lot sizing problem with remanufacturing options for a finite-horizon stochastic scenario. Finally, the work presented in Feng et al. (2013) analyzed a continuous-time recovery system for perishable products.

The studies by Dobos (2005, 2007) gave the first insights in the integration of the environmental effects into inventory models. Using the Arrow-Karlin model, the author analyzed the effects of emission trading on the production-inventory strategy of the firm. Through numerical examples the author proved an increase in inventory levels, and a smoother behavior of production rate. Later on, the study by Li and Gu (2012) extended the work of Dobos (2005, 2007) and explored the introduction of banking carbon allowances. The authors proved that allowance banking causes higher inventory levels and a smoother behavior on production rate. Besides the latter works, studies dealing with inventory and environmental constraints have mainly extended the EOQ-model in several directions. The authors in Bonney and Jaber (2011) present an extension of the EOQ model entitled the "Enviro-EOQ."In addition to traditional costs, they considered disposal and emission costs from transport. The authors concluded that when the environmental costs are introduced, the lot size is greater than the one provided by the traditional EOQ model. The work of Arslan and Turkay (2013) also extended the EOQ model, towards the integration of the sustainable concept. In their work, they presented five environmental management methods: 1) direct accounting, 2) carbon tax, 3) direct cap, 4) cap-and-trade and 5) carbon offsets. However, under approaches 1 and 2, the EOQ model does not change. The study of Hua et al. (2011) included an environmental damage cost in their model. Using a deterministic approach, they carried out an extension of the EOQ model. The authors determined the effect of the economic lot size, the carbon price, emissions and legislation on the total cost. The authors in Chen et al. (2013) also focused on the EOQ model. Their study is based on the traditional objective function, subject to an emission-cap. The authors proved that a cap is effective only when it is small enough to trigger a change in the quantity to order. In Bouchery et al. (2012) presented an extension of the EOQ model named "the Sustainable Order Quantity"(SOQ) model. A multi-objective formulation coupled with an iterative method which allows interaction with decision makers is presented. The work of Chen and Monahan (2010) presented an analysis of the impact of environmental policies on inventory levels. Based on a stochastic model with random demand and environmental impacts over a finite-horizon, the authors determined the optimal inventory policies. Ultimately, the authors proved that when organizations are working under a mandatory scheme, they tend to increase their inventory levels, causing significant environmental effects. Finally, in Toptal et al. (2014), the EOQ-model is extended by including three carbon regulation policies: 1) direct cap, 2) cap-and-trade and 3) carbon tax. The authors derive and compare the solution approach for a retailer's joint inventory control. They show that for any given policy, there is a cap-and-trade policy that will lower cost and emissions.

The stochastic scenario has been studied by Song and Leng (2012). The authors investigated the newsvendor problem under a carbon emission-tax, a direct-cap and emission trading scheme. For each approach, the optimal production quantity and the expected profit is given. Using the same approach, the study by Hoen et al. (2012) incorporates multiple emission reduction policies into inventory control. The authors seek to reduce carbon emissions by selecting transport modes. A recent work on green inventory presented by Rosič and Jammernegg (2013) explores companies' decisions considering transport carbon emission. Based on the newsvendor framework, the author presents a basic dual outsourcing model. The work of Zhang and Xu (2013) also extended the newsvendor problem. The authors studied the multi-item production planning under a cap-and-trade scheme. The authors in Liu et al. (2013) derive the optimal order quantity for retailers facing random demand and subject to a cap-and-trade scheme. Their analysis concluded that the order quantity is determined by carbon prices rather than by the emission-cap. Recently, the authors in García-Alvarado et al. (2014) dealt with an infinite-horizon product recovery problem subject to a cap-and-trade scheme. The authors characterize the inventory policy and describe some of the effects of environmental factors on the structure. Nevertheless, given the curse of the dimensionality the authors were not able to extend their results to larger instances. In this paper, we extend the work of García-Alvarado et al. (2014) to a finite-horizon.

### 3.3 Objectives and Model Formulation

In this paper, we consider a finite-horizon product recovery system subject to environmental constraints. For now, we not only determine the replenishment manufacturing and remanufacturing quantities, but also determine the proper amount of allowances to acquire or to sell in order to respect environmental constraints. Hence, our main objectives are 1) to extend previous knowledge of inventory control and recovery systems by incorporating environmental constraints and exploring the impact on the optimal policy; and 2) to contribute to the understanding of the role of inventory control on emission reduction, by establishing a carbon management policy, and analyzing the impact of inventory control on improving the environmental performance of a company.

We consider a stochastic closed-loop system subject to two environmental constraints: 1) a cap-and-trade system and 2) a minimal remanufacturing requirement. Through a cap-and-trade mechanism, a number of carbon allowances (emission-cap) is allocated to a firm. Hence, the total amount of emissions generated must be below the emission-cap. Therefore, the company can purchase or sell the excessive amount of allowances in the trading market. In particular, a loose emission-cap or a company stopping production to trade its allowances would result in a firm with sufficient credits to not reduce its emissions and still get benefits from the sale of allowances. To prevent those scenarios, the sale of carbon credits is then only possible when the company achieved a $\beta$-emission reduction from the previous period. On the other hand, under a minimal remanufacturing requirement policy at each period a minimal quantity of returns must be remanufactured. We consider this as a major managerial strategic consideration in the scenario in which remanufacturing is more expensive than manufacturing. If the decisions of a company are merely cost-driven, remanufacturing obviously will not occur. Thus, the legislation introduces product recovery by force.

The system (Figure 3.1) is a periodic-review process modeled in discrete time. Let $T$ be the full horizon length. As shown in the figure, the system has two stock points 1) remanufacturable and 2) serviceable. Let $x_t^R$ and $x_t^S$ denote the remanufacturable and serviceable inventory levels, respectively. Each inventory has a capacity $\kappa^{aR}$ and $\kappa^S$. The remanufacturable inventory is replenished by returns. Demand is satisfied by the serviceable inventory which can be replenished by manufacturing and remanufacturing. Returns ($R_t$) and demands ($D_t$) in each period $t$ are independent, non-negative, discrete random variables with a probability distribution $\phi(j) = Pr[R_t = j]$ and $\phi(i) = Pr[D_t = i]$, respectively. Backlog is allowed up to a maximum quantity $\kappa^v$ with a penalty $v$. When unfilled demand exceeds $\kappa^v$, sales are lost at a cost $C_{ls}$. Let $p_t$ and $r_t$ denote the amount of brand-new and returns units manufactured and remanufactured, respectively. Manufacturing and remanufacturing have a production capacity denoted by $\kappa^p$ and $\kappa^r$, respectively. Lead-time for both activities is a single-unit period, i.e., orders raise serviceable inventory at the end of periods. The manufacturing and remanufacturing costs are stationary and comprise a fixed and a quantity-related production cost. There is also an environmental impact associated with each activity. Ultimately, holding costs, penalties (lost-sales and backorders), and environmental impacts are considered at the end of each period.

The dynamics of the system are the following. At the beginning of each period, inventory levels are reviewed. Then, the following decisions are made: 1) quantity to remanufacture, 2) quantity

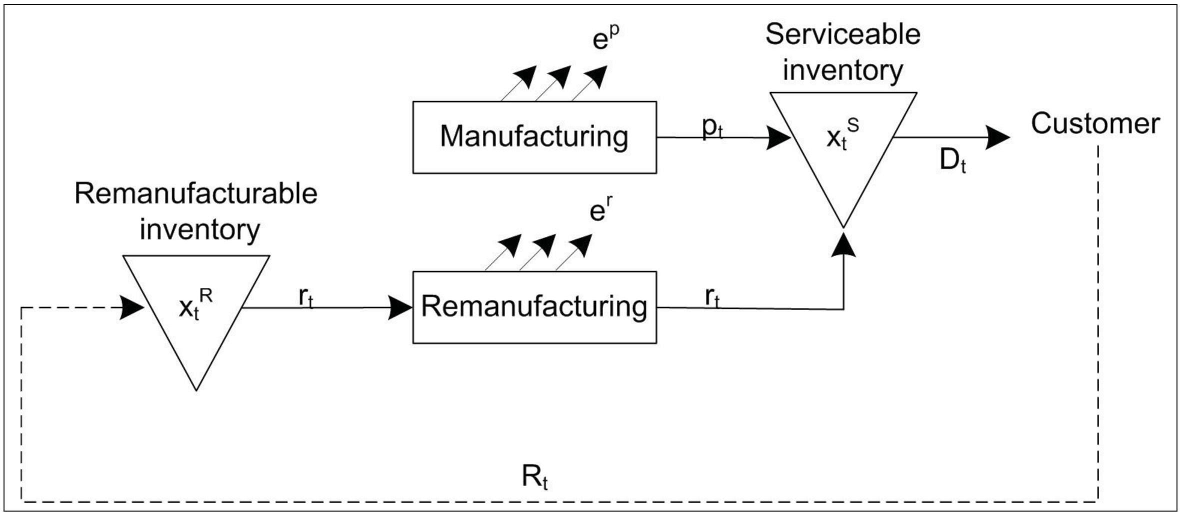


Figure 3.1 Closed-loop system

to manufacture, 3) the number of allowances to purchase, and 4) the number of allowances to sell. The aim is to determine the optimum replenishment manufacturing and remanufacturing quantities, and the carbon management strategy to minimize the total cost over the full horizon length. Notations used throughout this paper are summarized in Table 3.1.

The system is formulated as a finite-horizon dynamic problem. We use a backward recursive formulation in which the problem is solved at the end of the planning horizon and moves backward to the initial stage. The associated model is described below.

### 3.3.1 Stages and States

In the present formulation, the time periods $t \in T$ correspond to the stages. The state of the system at period $t$ is given by $s_t := (x_t^S, x_t^R, e_t, \varpi_t)$, where $e_t$ represents the amount of emissions banked at period $t$ and $\varpi_t$ the amount of emissions generated at the end of the previous period. The set of all possible states at each stage is captured by a matrix of size $N \times 4$, that is, $S := \{[0, \quad \kappa^S] \times [0, \quad \kappa^{aR}] \times [0, \quad E^c] \times [0, \quad E^c + \kappa^{e^+}]\}$. In addition to a cap-and-trade scheme, we include an alternative environmental mechanism; an emission-tax $C_e$, under this scheme a penalty is paid for each emission generated. There are four major decisions to make at each

Table 3.1 Notations

| **Parameters** | | **Costs** | |
|---|---|---|---|
| $\kappa^r$ | Remanufacturing capacity | $h^S$ | Holding cost per unit of serviceable product per period |
| $\kappa^p$ | Manufacturing capacity | $h^R$ | Holding cost per unit of remanufacturable product per period |
| $\kappa^S$<br>$\kappa^{aR}$ | Serviceable inventory capacity<br>Recoverable inventory capacity | $v$<br>$C_r$ | Shortage cost per unit<br>Remanufacturing cost per unit |
| $\kappa^v$ | Maximum amount of backlog allowed | $C_p$ | Manufacturing cost per unit |
| $\kappa^{e^+}$ | Maximum amount of allowances to purchase | $C_d$ | Disposal cost per unit |
| $\kappa^{e^-}$ | Maximum amount of allowances to sell | $C_{ls}$ | Lost sale cost per unit |
| $\phi(i)$ | $\Pr[D_t = i]$ | $\tau_r$ | Remanufacturing setup cost |
| $\phi(j)$ | $\Pr[R_t = j]$ | $\tau_p$ | Manufacturing setup cost |
| $E^c$ | Emission-cap (limit on carbon emissions) | $C^{a^+}$ | Carbon credit purchase price |
| $e^r$<br>$e^p$ | Amount of carbon emissions per remanufactured product<br>Amount of carbon emissions per manufactured product | $C^{a^-}$ | Carbon credit selling price |
| $\alpha$ | Minimal proportion of recoverable inventory to remanufacture per period | $C_e$ | Cost per emissions generated |
| $\beta$ | Minimum proportion of emission reduction between period $t$ and $t+1$ to allow selling of carbon credits at period $t$ | | |
| **Random variables** | | **Decision variables** | |
| $D_t$ | Stochastic demand in period $t$ | $p_t$<br>$r_t$ | Quantity of products manufactured in period $t$<br>Quantity of products remanufactured in period $t$ |
| $R_t$ | Stochastic returns in period $t$ | $a_t^+$<br>$a_t^-$ | Carbon credits bought in period $t$<br>Carbon credits sold in period $t$ |

period: $r_t, p_t, a_t^+$, and $a_t^-$. Let $d_{s_t}(\pi)$ be the set of decisions $d_{s_t}$ for each state $s_t \in S$ at a given period $t$ according to a policy $\pi$. Then, $d_{s_t}(\pi) := (r_t, p_t, a_t^+, a_t^-)$.

Figure 3.2 illustrates the transition between states given a policy $\pi$. There might be several possible policies, denoted by the set $\Pi$, $\pi \in \Pi$.

The transition from state $s_t$ to state $s_{t+1}$ is the result of $d_{s_t}(\pi)$ and the random variables. The probability of transition is defined as the joint probability of the random variables, namely demand and returns, that is, $P_\pi(s_t, s_{t+1}) = \sum_{j=0}^{\infty} \sum_{i=0}^{\infty} Pr[D_t = i] Pr[R_t = j]$. The transition from state $s_t$ to $s_{t+1}$ is described by Equations (3.1) to (3.4).

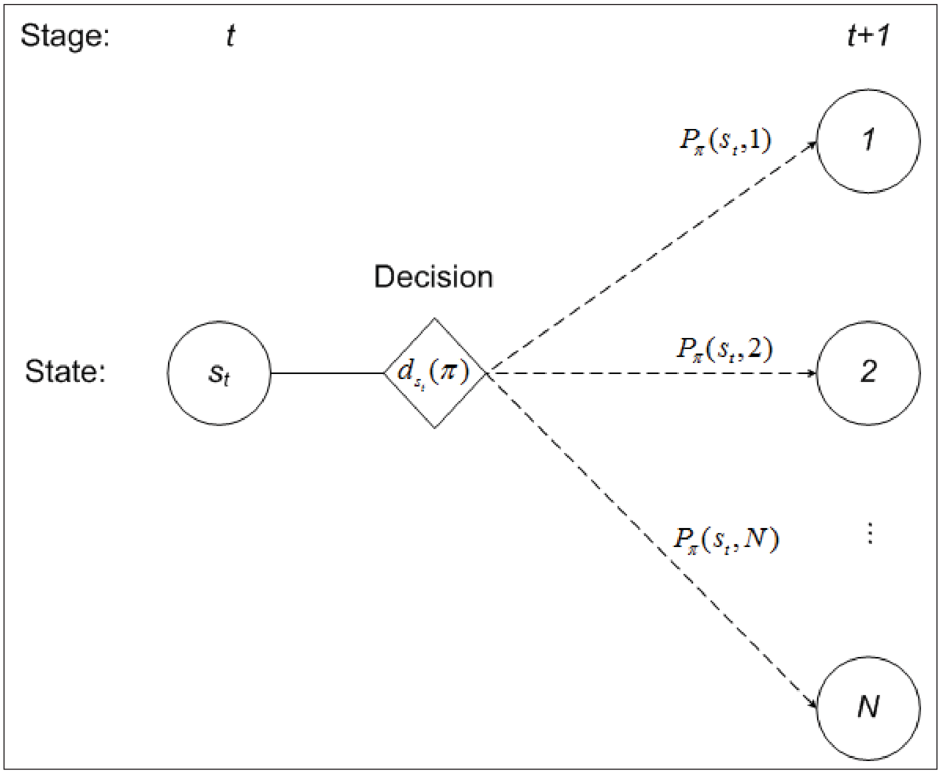


Figure 3.2 Decision diagram

$$x^R_{t+1} = \min\{x^R_t + j - r_t, \kappa^{aR}\} \tag{3.1}$$

$$x^S_{t+1} = \min\{\max\{x^S_t - i, -\kappa^v\} + p_t + r_t, \kappa^S\} \tag{3.2}$$

$$e_{t+1} = e_t - \eta_t(x^S_t, x^R_t, p_t, r_t) - a^-_t + a^+_t \tag{3.3}$$

$$\varpi_{t+1} = \eta_t(x^S_t, x^R_t, p_t, r_t) \tag{3.4}$$

Let $\eta_t(x^S_t, x^R_t, p_t, r_t)$ denote the emissions generated by the actions taken according to policy $\pi$. Then, the sub-state $\varpi_t$ is used as an auxiliary state to ensure that the sale of carbon credits is only made when emissions have been previously reduced.

### 3.3.2 Value Function

A policy will be defined according to the expected cost function $f_t(s_t, d_{s_t}(\pi))$. This is composed of: 1) production costs, 2) holding costs and penalties, and 3) carbon allowance trading cost.

#### Production Costs

Manufacturing and remanufacturing costs are given by Expressions (3.5) and (3.6), respectively. Production costs consider a setup cost per batch and a quantity-related cost. Setup costs are only considered when manufacturing (remanufacturing) orders are greater than zero:

$$\delta_t(p_t) = \begin{cases} \tau_p + C_p p_t, & p_t > 0 \\ 0, & \text{otherwise} \end{cases} \tag{3.5}$$

$$\gamma_t(r_t) = \begin{cases} \tau_r + C_r r_t, & r_t > 0 \\ 0, & \text{otherwise} \end{cases} \tag{3.6}$$

#### Holding Costs and Penalties

Let $H_t(x_t^R, r_t)$ denote the expected holding and disposal costs for remanufacturable inventory. A cost $h^R$ per unit will be charged for all returned products remaining in the inventory at the end of the period. In addition, if the remanufacturable inventory level exceeds its capacity $\kappa^{aR}$, surplus products are disposed of at a cost $C_d$ per unit disposed.

$$H_t(x_t^R, r_t) = h^R \sum_{j=0}^{\kappa^{aR}+r_t-x_t^R} (x_t^R + j - r_t)\phi(j) + C_d \sum_{j>\kappa^{aR}+r_t-x_t^R}^{\infty} (x_t^R + j - \kappa^{aR} - r_t)\phi(j) \tag{3.7}$$

The expected holding costs and penalties for serviceable products $L_t(x_t^S, r_t, p_t)$ are given by Expression (3.8). This Expression consists of 1) the holding cost $h^S$ that is charged to all serviceable products remaining in the inventory at the end of the period, 2) the expected shortage cost, a penalty $v$ will be charged to the sum of unfilled demands lower than the maximum quantity of backorder allowed $\kappa^v$, and 3) the expected lost-sale cost given by a lost-sale penalty $C_{ls}$ associated with the unfilled demand going above $\kappa^v$.

$$L_t(x_t^S, r_t, p_t) \quad = \quad h^S \sum_{i=0}^{x_t^S} [x_t^S - i + p_t + r_t]^+ \phi(i) + v \sum_{i > x_t^S}^{x_t^S + \kappa^v} (i - x_t^S)\phi(i) + C_{ls} \sum_{i > x_t^S + \kappa^v}^{\infty} (i - x_t^S)\phi(i) \quad (3.8)$$

Where $[x]^+ = \max\{x, 0\}$.

**Carbon Allowance Trading Cost**

The total amount of emissions generated over the period $t$ for the set of activities $(p_t, r_t)$ is defined by $\eta_t(x_t^S, x_t^R, p_t, r_t)$.

$$\eta_t(x_t^S, x_t^R, p_t, r_t) = e^p p_t + e^r r_t \quad (3.9)$$

Let $\rho(e_t)$ denote the cost for the emissions generated. The first term represents the expected cost of the emissions generated. The second and third terms represent the expected quantity of allowances to buy or to sell, respectively. The value of $C_e$, $C^{a^+}$, and $C^{a^-}$ depend on the environmental policy. A cap-and-trade scheme might assume an emission cost ($C_e$) equals zero.

$$\rho(x_t^S, x_t^R, e_t, p_t, r_t) = C_e \eta_t(x_t^S, x_t^R, p_t, r_t) + C^{a^+} a_t^+ - C^{a^-} a_t^- \quad (3.10)$$

**Cost Function**

Let $f_t(x_t^S, x_t^R, e_t, \varpi_t, d_{s_t}(\pi))$ denote the expected cost at period $t$ when the system is operated under the policy $\pi \in \Pi$ given the state of the system $(x_t^S, x_t^R, e_t, \varpi_t)$ at the beginning of period $t$.

$$f_t(x_t^S, x_t^R, e_t, \varpi_t, d_{s_t}(\pi)) = \delta(p_t) + \gamma(r_t) + H(x^R, r_t) + L(x^S, r_t, p_t) + \rho(x_t^S, x_t^R, e_t, p_t, r_t) \quad (3.11)$$

The objective is to determine the policy $\pi \in \Pi$ that minimizes the total expected cost over the planning horizon.

$$\min_{\pi \in \Pi} \mathbb{E} \sum_{t=1}^{T+1} f_t(s_t, d_{s_t}(\pi)) \tag{3.12}$$

The value function can be rewritten into the backward recursive function given by Expression (3.13). This expression affirms that the best policy $\pi$, is calculated by minimizing the summation of the best policy at the current state at stage $t$, plus the expected value at the following period.

$$V_t(s_t) = \min_{\pi \in \Pi} \{ f_t(s_t, d_{s_t}(\pi)) + \mathbb{E} V_{t+1}(s_{t+1}) \} \tag{3.13}$$

with $f_{T+1}(s_{T+1}, d_{s_{T+1}}(\pi)) \equiv 0$, as a boundary condition.

The above model is subject to the following constraints: manufacturing and remanufacturing quantities at each period must be less than inventory levels and production capacities:

$$p_t \leq \kappa^p \tag{3.14}$$

$$r_t \leq \min\{x_t^R, \kappa^r\} \tag{3.15}$$

Carbon allowances purchased or sold must be less than the maximum amount permitted. The parameter $\kappa^{e^+}$ denotes the maximum amount of allowances to sell. Since $a_t^+$ is the quantity purchased at period $t$. Constraint (3.16) ensures that the quantity purchased at period $t$ does not exceed the maximum quantity. The set of constraints (3.17) to (3.19) ensures it is possible to sell allowances at period $t$ only when emissions from the previous period were reduced at least by $\beta$. The parameter $\beta$ is a proportion which represents a minimal reduction of emissions and $M$ is a large positive constant. Constraint (3.19) ensures the minimal $\beta$ reduction.

$$a_t^+ \leq \kappa^{e^+} \tag{3.16}$$

$$a_t^- \leq \kappa^{e^-} y \tag{3.17}$$

$$\frac{\varpi_t - \varpi_{t+1}}{\varpi_t} \geq \beta + M(y-1) \tag{3.18}$$

$$y \geq 0, \quad y \leq 1, \quad \text{and integer} \tag{3.19}$$

Emissions banked at each period must be less than the emission-cap.

$$e_t \leq E^c \tag{3.20}$$

Decisions must be integers and greater than the minimum requirement.

$$r_t \geq \alpha x_t^R \quad \text{and integer} \tag{3.21}$$

$$p_t \geq 0, a_t^+ \geq, a_t^- \geq 0 \quad \text{and integer} \tag{3.22}$$

State variables $x_t^R$, $e_t$ and $\varpi_t$ must be non-negative.

$$x_t^R \geq 0, e_t \geq 0, \varpi_t \geq 0 \tag{3.23}$$

## 3.4 Exact Solution: Dynamic Programming

The problem presented in Section 3.3 is a combinatorial optimization problem, where at each planning period a set of decisions must be made. Dynamic programming is a technique that can be used to obtain the optimal solution of combinatorial problems. Nevertheless, the number of iterations required to reach the optimal solution depends on the state and the solution space. We conducted a pilot study to gain more knowledge about the behavior of the system and resolution time. Three instances (Table 3.2) were studied over a 12 period planning horizon. The instances differ in the number of possible solutions and the size of the state space. The first and third instances are, respectively, the smaller and the larger scenarios. The rest of the parameter values are shown in Table 3.3.

Table 3.2 Instances studied through dynamic programming

| Instance | Initial State $[x_0^R, x_0^S, e_0, \varpi_0]$ | Upper bounds per variable $[\kappa^r, \kappa^p, \kappa^{e^+}, \kappa^{e^-}]$ | $\kappa^v$ | Upper bound per state $[\kappa^{aR}, \kappa^S, E^c]$ |
|---|---|---|---|---|
| 1 | [0, 0, 2, 0] | [4, 2, 2, 2] | -1 | [4, 8, 2] |
| 2 | [5, 3, 7, 0] | [5, 3, 3, 3] | -1 | [5, 3, 7] |
| 3 | [0, 10, 10, 0] | [6, 10, 10, 10] | 0 | [8, 12, 10] |

Table 3.3 General parameters

| Parameter | Value | Parameter | Value | Parameter | Value |
|---|---|---|---|---|---|
| $C_p$ | \$90/tonne | $C_{ls}$ | \$179/tonne | $\tau_r$ | \$0 |
| $e^r$ | $1tCO_2$/tonne | $C^{a^+}$ | $\$1.36/tCO_2$ | $C_r$ | \$130/tonne |
| $h_S$ | \$15/tonne | $\tau_p$ | \$0 | $e^p$ | $2tCO_2$/tonne |
| $\beta$ | 0.2 | $C_d$ | \$0 /tonne | $h_R$ | \$1.6/tonne |
| $v$ | \$115/tonne | $C^{a^-}$ | $\$1.32/tCO_2$ | $\alpha$ | 0.1 |

We consider demand and returns are discrete and follow a trapezoidal and triangular distribution, respectively:

$$\phi(i)=\Pr[D_t = i] = \begin{cases} \frac{i}{20}, & 1 \leq i \leq 4 \\ \frac{9-i}{20}, & 4 < i \leq 8 \\ 0, & \text{otherwise} \end{cases} \qquad \phi(j)=\Pr[R_t = j] = \begin{cases} \frac{j+1}{9}, & 0 \leq j \leq 2 \\ \frac{5-j}{9}, & 2 < j \leq 4 \\ 0, & \text{otherwise} \end{cases}$$

The results suggest a reduction in manufacturing replenishment quantities, dropping in average 23% the amount of emissions generated, but increasing costs by 3%. However, 20% of cost increment results from the allowance purchase, thus operational costs are only raised by 2.5%.

Due to the restricted size of state and action spaces, the results are not enough to determine a significant change on remanufacturing replenishment quantities. Then, despite there is evidence that inventory policies are affected by environmental policies, a deeper study with bigger instances is necessary.

Regarding dynamic programming performance, according to the results CPU time passed from 1.13 s in Instance 1 to 501.55 s in Instance 3. Then, resolution time increases with the size of the problem. Since dynamic programming can only solve relatively small instances of our problem in a considerable computational time it is not possible to explore larger scenarios as higher emission-quotas. It seems worthwhile to extend the experiments and to gain experimental knowledge. To overcome this computational obstacle, we develop a genetic algorithm (GA).

## 3.5 Approximated Solution: Genetic Algorithm

GAs have proven to be an efficient method for solving diverse combinatorial problems in a reasonable amount of time, including the problem of inventory control. In this section we present a GA to determine at each period a set of decisions $(r_t, p_t, a_t^+, a_t^-)$ which minimize the total cost.

### 3.5.1 GA Structure

Genes of our GA are real-coded, and represent a decision to be made. Then, based on $d_{s_t}(\pi)$, chromosomes consist of an array of a size equals to the total number of decisions to be made over the planning horizon $T$. Decisions are grouped by period in the order: $r_t, p_t, a_t^+, a_t^-$, giving a total chromosome length of $4T$, i.e.:

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $r_1$ | $p_1$ | $a_1^+$ | $a_1^-$ | $r_2$ | $p_2$ | $a_2^+$ | $a_2^-$ | ... | $r_T$ | $p_T$ | $a_T^+$ | $a_T^-$ |

Decisions in period 1

Our GA begins by randomly generating an initial population of size $P$, in the following way: considering at each period upper bounds per decision variable, the available remanufacturable inventory, and the emissions banked, random decisions are made in the order 1) remanufacturing, 2) manufacturing, 3) allowances to buy, and 4) allowances to sell. Afterwards, the fitness of each individual is evaluated by the Expression (3.11). Therefore, given the high risk of building unfeasible chromosomes, there is an embedded repair function in the fitness evaluation. Hence, when a chromosome is evaluated, its feasibility is tested first. If a chromosome fails the test, the genes preventing it from being feasible are changed to their closest feasible value. After population initialization, reproduction actions follow.

Reproduction begins by choosing two random individuals for crossover. Each individual of the population has the same chance to be selected. If the same individual is selected twice, the last element is discarded, and a new parent is selected. This process continues until both parents are different. Afterwards, crossover is performed with a probability $CR$ between parents. For each pair of parents selected, one offspring is built. The crossover activity is a one-point crossover. To avoid losing information, the crossover-point is a random multiple of the number of decision variables per period (i.e., 4). The first parent gives to its offspring its first half and the second parent, its second half. In order to prevent loss of diversity, when the genotype of two parents is the same, an offspring is generated randomly. This procedure continues until $P$ offsprings are built. Offsprings can be mutated with probability $MR$. Three equally probable mutations might be performed: 1) $gene_{new} = gene_{old} + 1$, 2) $gene_{new} = gene_{old} - 1$, and 3) $gene_{new} = gene_{old}(1-x) + gene_{old}(2xu)$, inspired from Sánchez et al. (2010). The value of $x \in (0,1)$ is defined from the beginning. The choice between the set of mutation operators is made according to a random value $u \sim U(0,1)$.

After reproduction is finished, the new generation is built based on the fitness values and the preservation of diversity. If the genotype of an offspring is the same as that of any existing individual, the offspring does not enter the new population. An offspring will enter the new population if the fitness is better than at least one other member of the old population. When the fitness is not better that any individual of the old population, the offspring enters the new population with probability $r$. If an offspring enters the new population, the replacement of an old individual will be made according to the following sequence 1) determine a list of genotype duplicates and replace from the list the individual with the worst fitness; 2) if all individuals are different, determine fitness duplicates, and replace the best fitness duplicate; and 3) if there is no duplicate element (genotype or fitness), replace the individual with the worst fitness. The GA stops when any of the stop criteria is met: 1) the number of maximum iterations $N$ has been reached, or 2) the fitness value has not improved for $G$ times.

We conducted a sensitivity analysis to examine the performance of the GA through different parameter values. The parameters playing a key role in the performance are population size ($P$), mutation rate ($MR$), crossover rate ($CR$) and stop criteria ($G$). The performance of the GA is measured by the gap between the optimal solutions and the function values obtained by the GA. The maximal number of iterations ($N$) was fixed to 1000, and the noise factor ($x$) to 0.2. From the results, the GA gives an average error of 12.52 units and solves the problem in average time of 2.00$s$. The sensitivity analysis provides as best parameter settings: 1) $CR$=0.94, 2) $MR$= 0.16, 3) $P$= 225, and 4) $G$=240.

### 3.5.2 Preliminary Study

In the following, we perform a preliminary study to evaluate the performance of the GA. We consider that remanufacturing is less expensive and greener than manufacturing. In reality, the case study is a larger instance of the ones in Section 3.4. We assume a 24 planning horizon with $x_0^R = 3$ and $x_0^S = 5$. We use the GA parameter setting obtained in the previous section. The parameter settings are summarized in Table 3.4, demand and returns are distributed as in Section 3.4.

Table 3.4 General parameters

| Parameter | Value | Parameter | Value | Parameter | Value |
|---|---|---|---|---|---|
| $C_p$ | \$900/tonne | $C_{ls}$ | \$10000/tonne | $\tau_r$ | \$0 |
| $e^r$ | 0.6$tCO_2$/tonne | $C^{a^+}$ | \$-/$tCO_2$ | $C_r$ | \$1300/tonne |
| $h_S$ | \$150/tonne | $\tau_p$ | \$0 | $e^p$ | 12$tCO_2$/tonne |
| $\beta$ | 0.2 | $C_d$ | \$0 /tonne | $h_R$ | \$16/tonne |
| $v$ | \$1430/tonne | $C^{a^-}$ | \$-/$tCO_2$ | $\alpha$ | 0.1 |

The results show that there is no change in the inventory policy since the most economic decision is also the least polluting. Then, when establishing environmental strategies, the system would be still using the same inventory policy until it is no longer possible to produce the established manufacturing and remanufacturing amounts. In this case, first the quantity to manufacture is gradually reduced as the environmental-constraint becomes more severe. After manufacturing is completely stopped, the quantity to remanufactured is gradually decreased until all sales are lost.

Regardless of the expected behavior, we perform an analysis to determine how much the emission-cap can be reduced while keeping a service level higher than 80% (below this, the system is considered infeasible). We study the emission-cap in a range of 640 t$CO_2$/horizon to 80 t$CO_2$/horizon, given a mean value of 669 t$CO_2$/horizon when environmental constraints are not included. According to Figure 3.3a, it is possible to reduce the total quantity of the system's emissions by 40% with a service level greater than 80%. Moreover, from Figure 3.3b it is noticed that the service level has the same behavior that the quantity of emissions generated (Figure 3.3a). This is because emissions generated by manufacturing and remanufacturing are linear and depends of the amount produced.

We also study the effect of the carbon allowance price. For this, we explore the changes in the replenishment decisions for carbon allowance prices between $\$5/tCO_2$ and $\$350/tCO_2$. Figure 3.4 shows the cumulative cost according to the carbon allowance price. The results indicate that while there is an increase in the price, the quantity of allowances to purchase is always the same in the different scenarios. As result, the increase in the total cost will be proportional to the increase in the allowance price. Hence, when remanufacturing is the cheapest and more environmentally friendly activity, a cost-minimization approach should be taken. Moreover, if it were still necessary to reduce the amount of carbon emissions without losing sales, the only solution would be to switch to a cleaner technology.

If an emission-tax is integrated to reduce the carbon footprint of a company, and the environmental-penalty increases the production cost in a way that manufacturing still is less expensive than

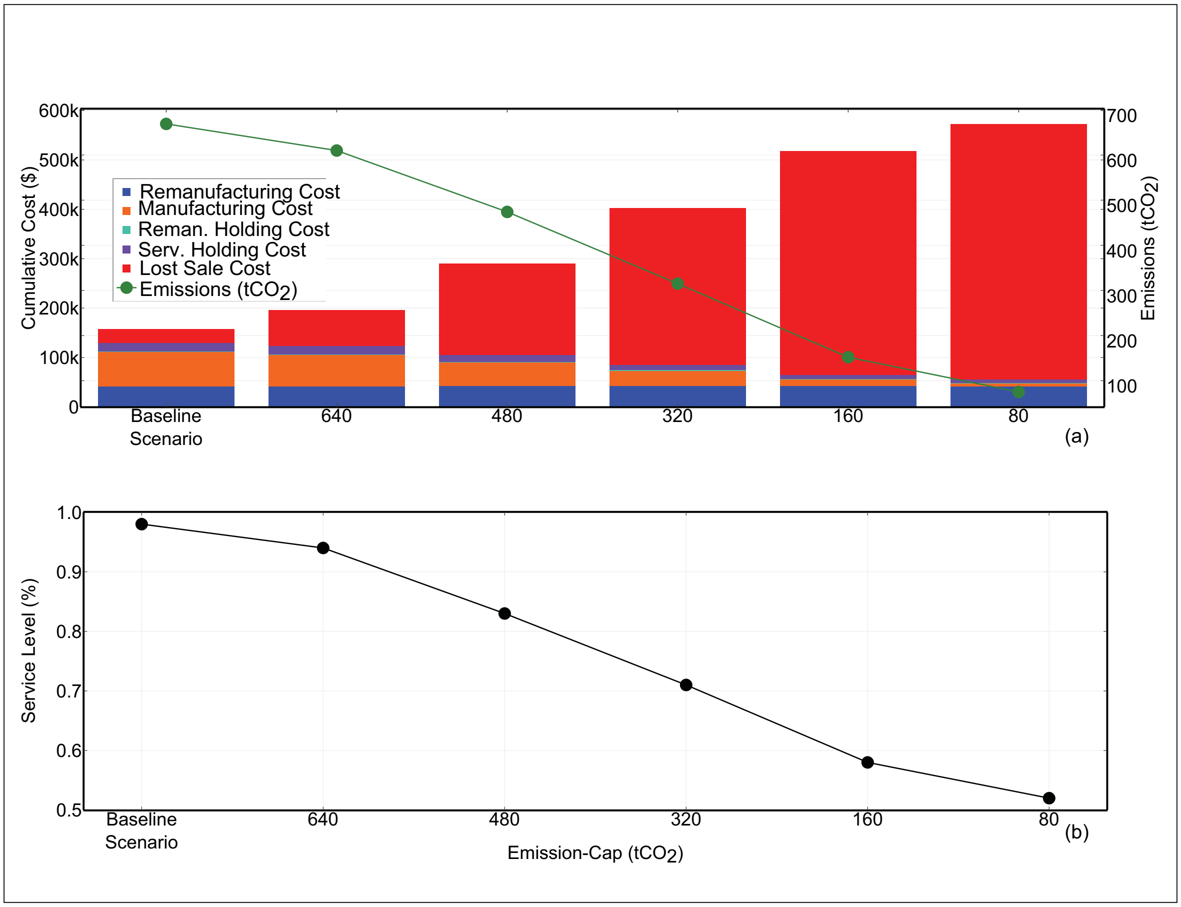


Figure 3.3 Emission-cap analysis: a) cumulative costs and emissions, b) service level

remanufacturing; there will be no change in the inventory control policy. Manufacturing will be preferred over remanufacturing and the system will continue manufacturing until the production cost is more expensive than losing a sale. At that point, the system will begin to lose all sales. On the other hand, in the case that the remanufacturing cost plus the emission-tax is less expensive than manufacturing, the system will behave as stated in Simpson (1978) or a variant, and as the emission-tax increases, the system will stop manufacturing and then remanufacturing. Given the triviality of the scenario, an emission-tax approach was not studied.

In relation to the performance of the GA, we performed 30 runs for each scenario, the average CPU time is 8.71 s with a standard deviation of 0.58, a minimum value of 2.12 s and a

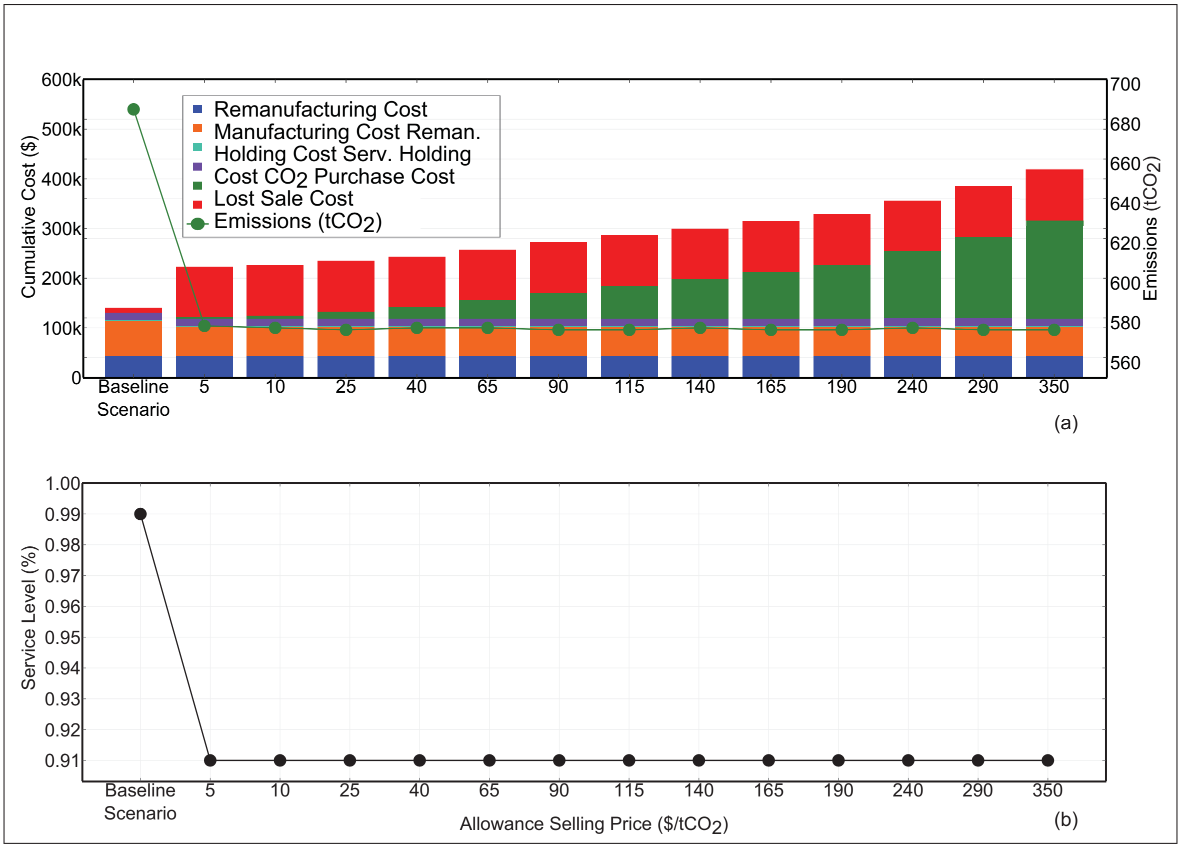


Figure 3.4 Carbon allowance price analysis: a) cumulative costs and emissions, b) service level

maximum value of 18.69 s. Then, the GA reduces by more than 98% the computational time regarding the largest instance tested in Section 3.4.

## 3.6 Numerical Examples

Considering the case study in section 3.5.2, in this section we present extended examples. The scenarios under study only consider the case where there are two processes, one low-cost and polluting (manufacturing), and another expensive, but greener (remanufacturing). The systems that would exhibit this behavior are those which despite the fact that remanufacturing might save money on the purchase of virgin raw material, collection and transport costs from collection centers are additional costs of remanufacturing that manufacturing does not consider. Moreover, given the recent age of reverse channels, these could still not be optimized and can lead to loss of money. Meanwhile, the collection of material is only one of the multiple activities added to the production process of remanufacturing. In general, recovered material has different quality, and sorting is necessary to determine if the products are in the state of being remanufactured. Moreover, raw material must be cleaned before use. All of these processes are time and money consuming, and they may cause remanufacturing to be more expensive than the traditional manufacturing process. It will be expected that company in this situation will never conduct remanufacturing on its own. This context encourages setting a minimal remanufacturing requirement which forces the use of remanufacturing.

### 3.6.1 Parameter Settings

The GA uses the parameter values found previously. A sensitivity analysis is conducted focusing on the influence of the carbon allowance price, the emission-cap, the minimal remanufacturing quota, and allowance trading over the environmental performance. The horizon length of each simulation is 24 planning periods with the allowance price and the environmental impact of processes constant in $T$.

The numerical examples are built based on the literature and the California Cap-and-Trade Program. For 2014, the California Cap-and-Trade has fixed a minimum selling price of \$11.34/t$CO_2$. Neverthless, recently in other allowance trading programs, such as the EU ETS, the price has been falling below \$7/t$CO_2$. Therefore, we decided to begin the analysis from an allowance price of \$5/t$CO_2$. The remaining scenarios help us to simulate the forthcoming years since the California Cap-and-Trade imposes a minimum selling price each year equal to the previous year's selling price plus an increase of 5% plus inflation. In general, an allowance purchase price of 3% higher than the selling price is considered.

Regarding the environmental impact of the different processes, we consider manufacturing 95% more polluting than remanufacturing, but manufacturing costs half the price. Parameters are summarized in Table 3.5, and demand and returns follow the same distribution as those in Section 3.4. Considering the latter parameter values, we conducted a first analysis of the system to establish the quantity of emissions generated over a period without a cap-and-trade mechanism. The results show a mean environmental contribution of 1,218t$CO_2$ over 24 time periods with a standard deviation of 102.44 units. The emission-caps to study correspond to the average value of 1,218 $\pm$ 5 standard deviations.

Table 3.5 General parameters

| Parameter | Value | Parameter | Value | Parameter | Value |
|---|---|---|---|---|---|
| $C_p$ | \$900/tonne | $C_{ls}$ | \$10000/tonne | $\tau_r$ | \$0 |
| $e^r$ | 0.6$tCO_2$/tonne | $C^{a^+}$ | Variable | $C_r$ | \$1800/tonne |
| $h_S$ | \$150/tonne | $\tau_p$ | \$0 | $e^p$ | 12$tCO_2$/tonne |
| $\beta$ | 0.2 | $C_d$ | \$0 /tonne | $h_R$ | \$16/tonne |
| $v$ | \$0/tonne | $C^{a^-}$ | Variable | $\alpha$ | Variable |

Table 3.6 summarize the minimum, maximum and control value for each parameter. For each scenario, 30 independent runs are performed, and only one parameter is changed at a time. To better understand the effect of each parameter, we force the system to satisfy most of the demand. To this end, we consider that the system does not have the ability to backorder (i.e., $k^v = 0$), we assign a high lost-sale cost, and all scenarios are pre-charged with $x_0^R = 3$ and $x_0^S = 5$. In the following, we refer to a baseline scenario as a system that is not subject to any environmental policy.

Table 3.6 Sensitivity analysis for parameters of interest

| Parameter | Minimum Value | Maximum Value | Control Value |
|---|---|---|---|
| $E^c$ | 705t$CO_2$/T | 1730t$CO_2$/T | 1525t$CO_2$/T |
| $C^{a^-}$ | \$5.00/$tCO_2$ | \$240/t$CO_2$ | \$10/t$CO_2$ |
| $\alpha$ | 0 | 1 | 0 |

In the following, we characterize the effect on cost, emissions and replenishment policies of a parameter change over the studied cases.

### 3.6.2 Emission-Cap Effect

The impact of a direct-cap without the possibility of trading allowances is set according to the baseline scenario. The results show that there are three zones where a system subject to a direct-cap can be found. The first zone is where a system has been granted with more emissions than the average amount generated in a cost-minimization context. Hence, given that the system does not get any benefit for reducing its emissions, in reality cutting emissions would increase costs, the system behaves as the baseline scenario where the replenishment strategy only supports manufacturing, and remanufacturing is never used. The second zone is where the system has been granted with a quantity of allowances around its average amount of emissions generated. In this zone, the inventory policy changes and remanufacturing is included in the activities. By making a trade-off between costs and the environmental impact, the emission-cap is respected while still minimizing the costs. Finally, the third zone is where the quantity of emissions granted has been cut down significantly. Thus, since the emission-cap is too tight, the system is not able to reduce its emissions to the desired cap. The only option left is to reduce the amount of emissions by interrupting manufacturing. This results in losing sales. In this zone, it is advisable to change the technology in order to reduce the environmental impact without compromising the service level.

In the case study, Figure 3.5 shows the different zones. The service level above an emission-cap of 910t$CO_2$/horizon is stable at 99%. Afterwards, the service level falls rapidly. Figure 3.6 shows how the inventory policy changes the portion of demand satisfied by each process as the emission-cap decreases.

According to our findings, the relationship between an emission-cap and the inventory policy can be summarized as: there is a specified emission-cap range within which inventory control can help to overcome the constraints of a cap-and-trade mechanism.

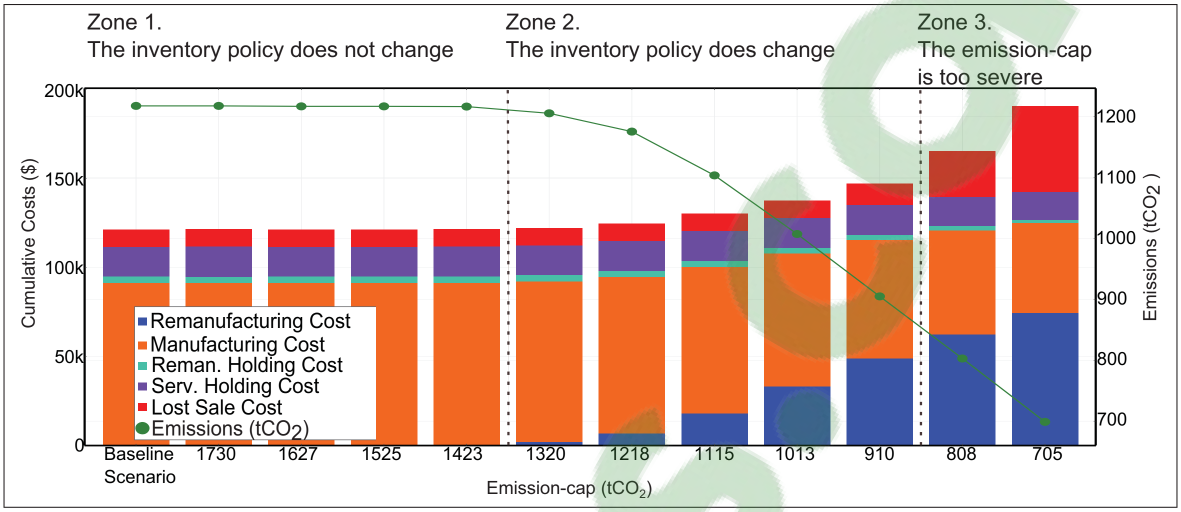


Figure 3.5 Emission-cap analysis

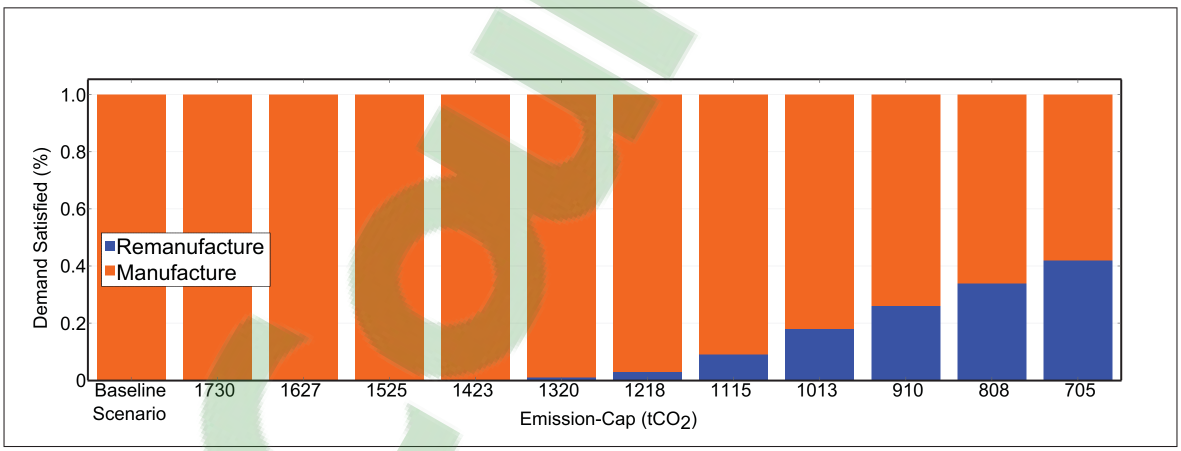


Figure 3.6 Percentage of demand satisfied by each process

### 3.6.3 Carbon Allowance Price Effect

We focus on determining the effect of the allowance price on replenishment decisions considering an emission-cap set to 1525t$CO_2$/horizon. The allowance selling price varies from \$5/t$CO_2$ to an extremely high price. This scenario can be seen as a mechanism where there is no emission-cap, and the company receives financial compensation for its efforts in reducing emissions. The more a company reduces carbon emissions, the more it gets compensated.

Figure 3.7 shows the total cost against the allowance selling price; the service level in all studied scenarios is 99%. The results indicate that the total cost decreases as the allowance price increases. Nevertheless, when the allowance price is between $\$5/tCO_2$ and \$140/t$CO_2$, there is no real reduction in the amount of emissions. The reduction in cost comes from the additional emissions granted to the system. Within this range, there is no change in the replenishment policy. However, when the price is equal to or greater than \$165/t$CO_2$, remanufacturing begins to be implemented. At that point, there is a change in the replenishment policy. It is important to notice that the system changes the replenishment policy when the environmental difference between processes multiplied by the allowance selling price reaches the price of the most expensive and greenest activity, i.e., remanufacturing. In other words, the financial benefit of the emission abatement pays for the switch to greener technology and due to this the inventory policy changes.

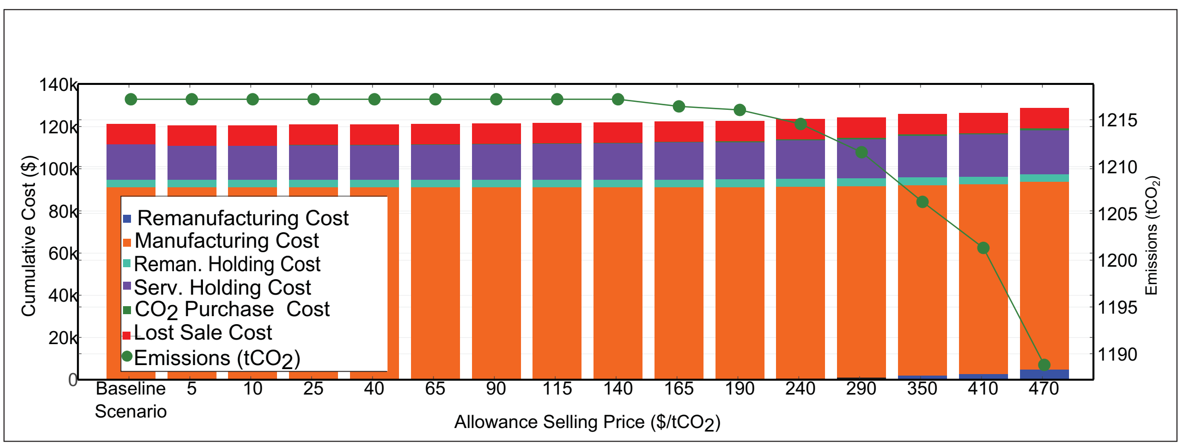


Figure 3.7 Allowance price analysis

Clearly, as the selling price rises, the system tries to cut more emissions. In the case study, given the large emission-cap, the system can operate without cutting down the quantity of emissions generated. Then, the emission abatement can be seen as a profit, which reduces as the amount of emissions generated reaches the minimal emissions requirement of 680t$CO_2$. Figure 3.8 shows the carbon abatement percentage behavior against the selling price.

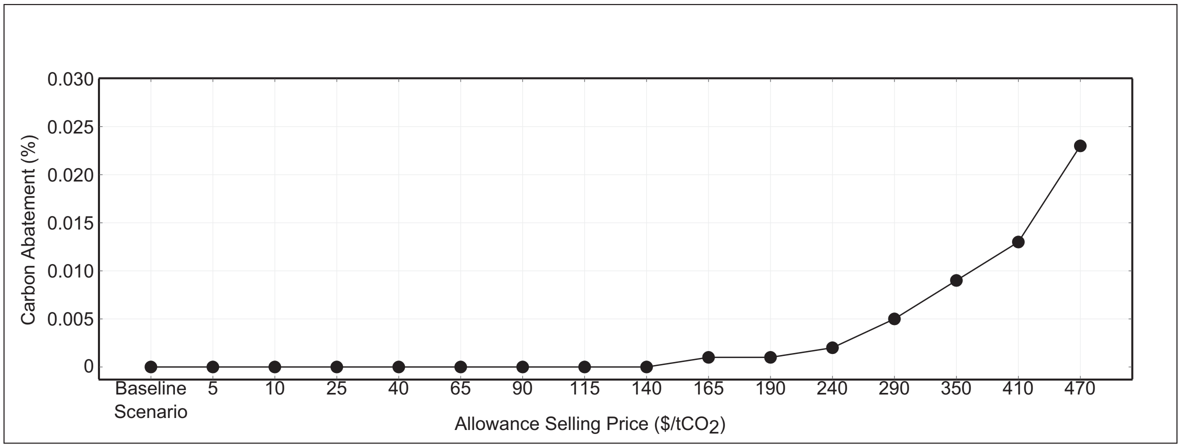


Figure 3.8 Carbon abatement

In the case study, we describe the influence of allowance prices in the inventory policy as: the allowance price will have an effect on the inventory policy if the financial compensation for reducing the emission absorbs the cost of the greenest activity.

### 3.6.4 Allowance Trading Effect

In the allowance trading scenario, we compare different emission-caps against a range of allowance selling prices. The decision to change the inventory policy, as well to manage carbon allowances, is driven by the emission-cap and the selling price.

We define three different zones along the allowance selling price, zones A, B and C. Zone A is where the price is not significant regarding the production cost. There, the emission-cap would drive the decisions. Zone B is where the selling price does not cover the cost of establishing cleaner technology, but the environmental benefit is on the scale of costs. Finally, zone C is where the environmental benefit covers the cost of introducing greener technology and the allowance selling price drives decisions. The three zones are clearly defined according to the production costs. Figure 3.9 shows the different zones for the selling price in the case study.

When the emission-cap is in the zone 1, the allowance selling price must be in zone C in order to make a modification in the inventory policy; otherwise, it is not profitable. The carbon

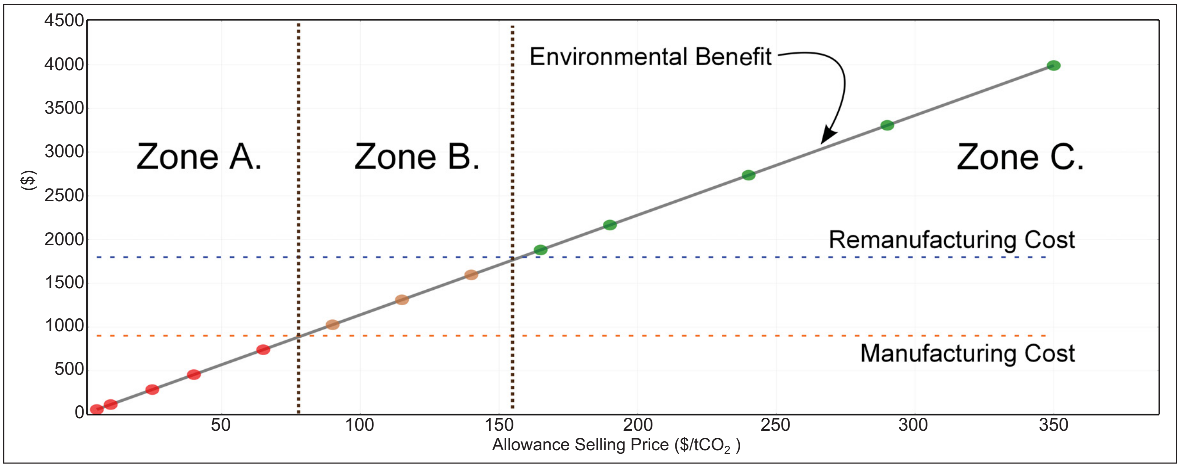


Figure 3.9 Environmental benefit of changing technology

management policy is simple as sell the over emission allocated. When the emission-cap is in the zones 2 or 3, decision-making is more critical than into zone 1. In zones 2 and 3, the allowance selling price has a high impact on how decisions are made. In the following, we analyze how decisions change in zones 2 and 3.

When the price is in zone A, the cap-and-trade mechanism is driven by the emission-cap. It means that the inventory policy is only modified when the emission-cap is in zone 3. Then, since the acquisition of the emission is not expensive, the inventory policy can help to ensure compliance with the law in a larger range of emission-cap values without reducing the service level. As the allowance price increases in zones B and C, the company will look forward to reducing its carbon emissions because of the financial benefit, and the change in the inventory policy will be made sooner for the emission-cap range. Hence, the inventory policy is changed immediately when the emission-cap is in zones 2 or 3. Nevertheless, as the allowance selling price continues to rise, the emission-cap strategy is similar to a direct-cap scenario where the inventory policy can help the industry in a smaller emission-cap range and, therefore, for a shorter time period without compromising the service level. Figure 3.10 shows how the inventory policy in the case study changes the proportion of demand satisfied by each process.

The results show the allowance selling price has a high impact on the amount of t$CO_2$ to purchase (Figure 3.11). The higher the selling price is, the more the resemblance of a cap-and-

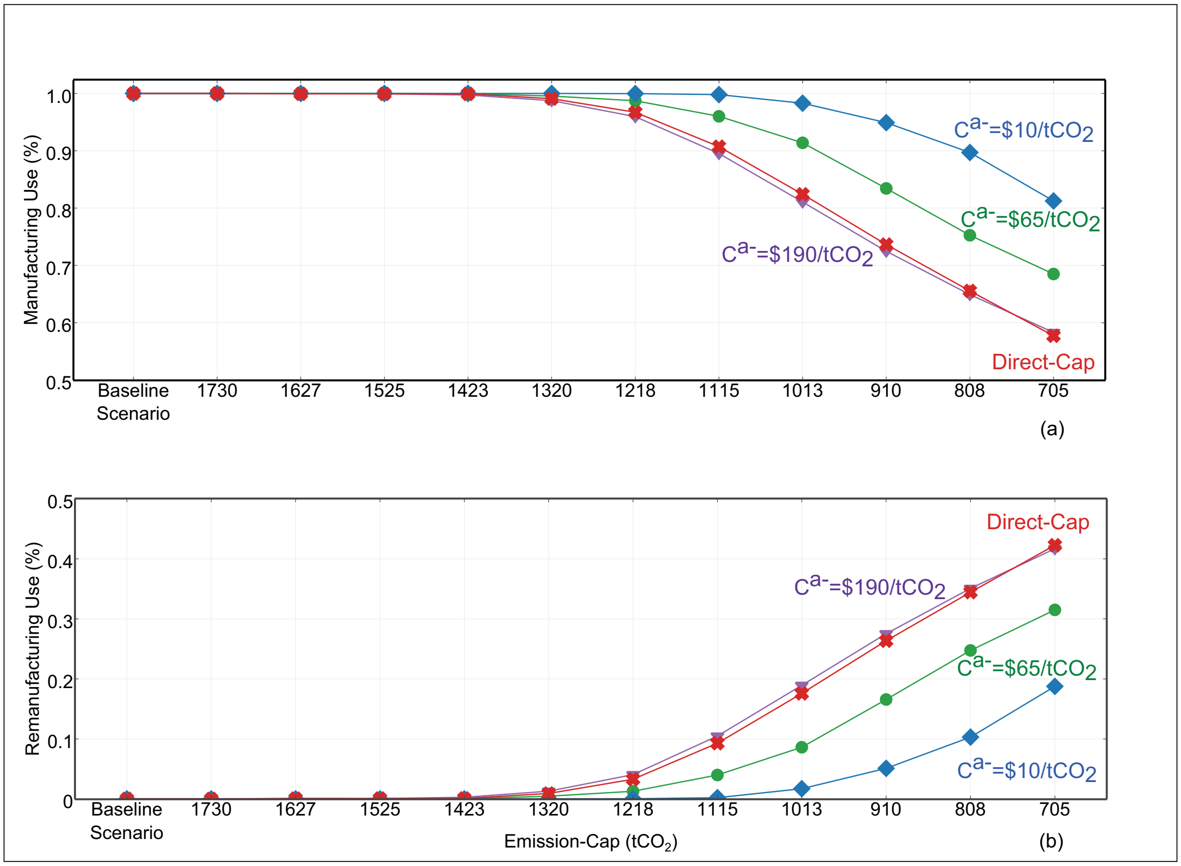


Figure 3.10 Percentage of demand satisfied by each process: a) manufacture, b) remanufacture

trade with a direct-cap approach is evident. The carbon management policy defined according to the allowance selling price is the following. In zone A, since the price is low, the system behaves as if there is not an environmental mechanism and all required allowances are bought; there is no sale of allowances. In zone B, the system starts to be implicated in the dynamics of the cap-strategy; purchase and selling of allowances is moderate. Ultimately in zone C, the company embraces the environmental mechanism; allowance selling is important, while allowance purchase is almost none.

Applying a cap-and-trade strategy allows a company to earn a profit by reducing their emissions, even without considering the growth in demand due to being a green industry. In opposite, a direct-cap approach would only force the company to reduce its emissions, and the cap should be well set in order to achieve substantial reductions. Hence, a cap-and-trade ap-

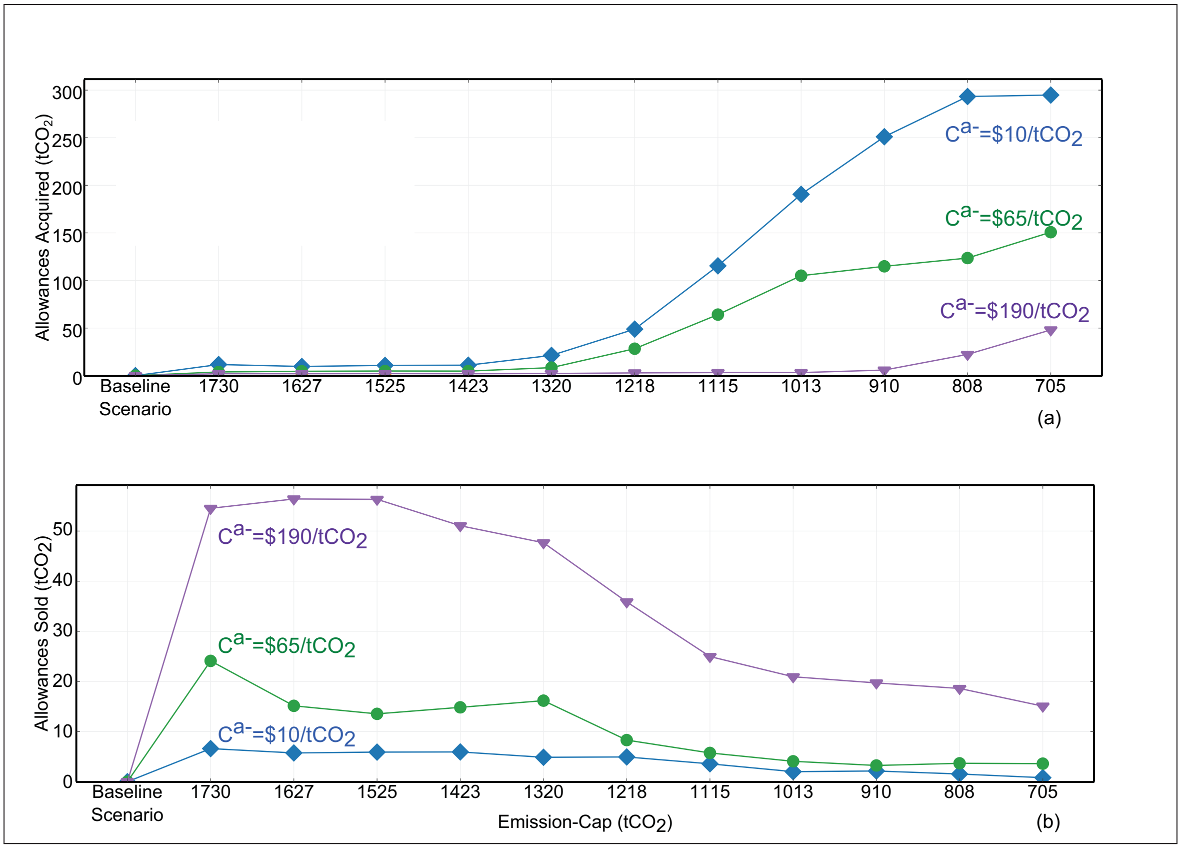


Figure 3.11 Carbon management on allowance trading: a) allowances acquired ($tCO_2$), b) allowances sold ($tCO_2$)

proach would be a preferable environmental mechanism, even if the cap is not well structured. Figure 3.12 shows the emission generation over different strategies. As can be seen, when the emission selling price is high (zone C), there is a negligible difference between the amount of emissions generated in a direct-cap and in a cap-and-trade mechanism. In addition, Figure 3.13 shows the reduction in cost by applying a cap-and-trade scheme. It can be seen that when the allowance price is low (zone A), because only the carbon management strategy is restructured in a way to maintain the same replenishment decisions, the total cost remains relatively stable compared to those of other prices. In contrast, when the price increases the total cost curves have a higher resemblance between them, but always remaining lower in cost than the direct-cap scenario. Thus, as cited in Toptal et al. (2014), the cap-and-trade strategy can help to reach the same emission abatement than a direct-cap scenario at lower cost.

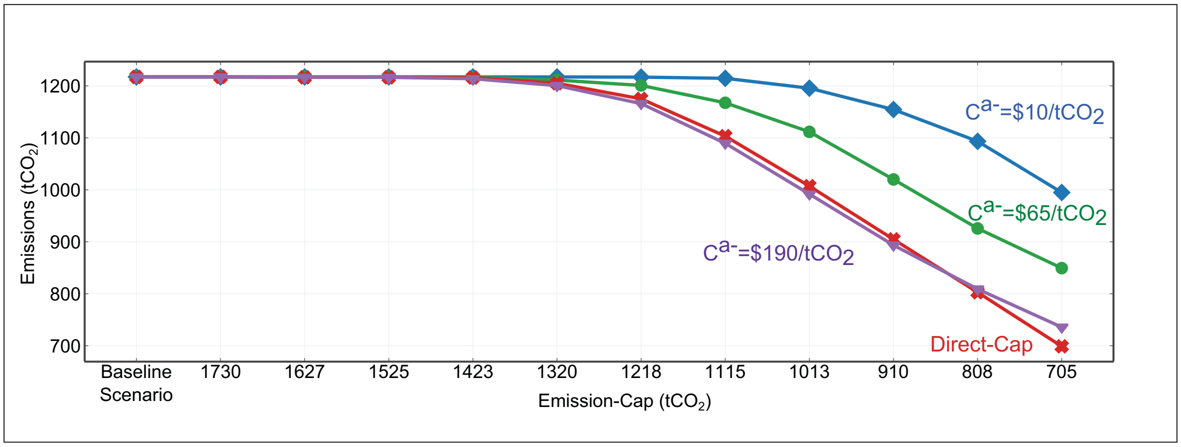


Figure 3.12 Impact of allowance trading on emission generation

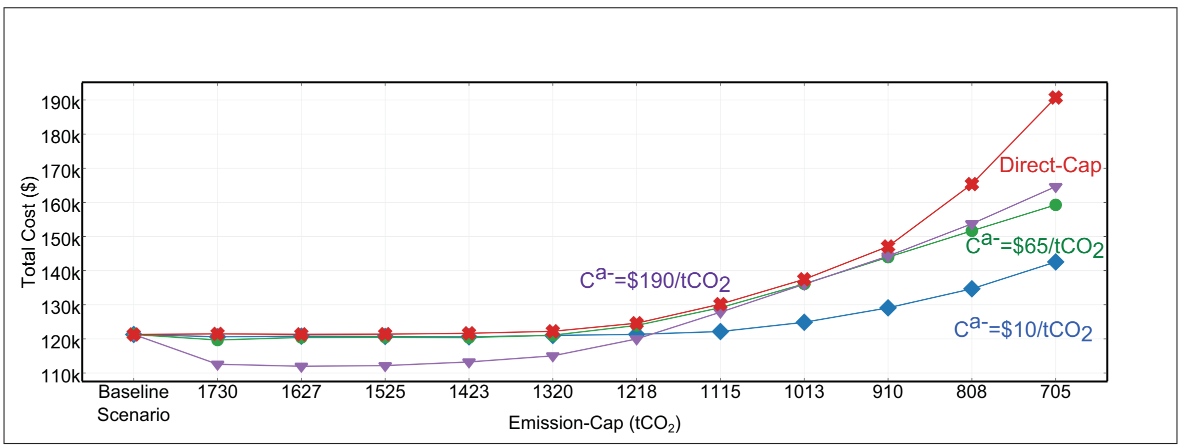


Figure 3.13 Impact of allowance trading on cost

In conclusion, the findings suggest that higher allowance prices would encourage companies to voluntarily participate in the dynamics of the carbon market.

### 3.6.5 Minimal Remanufacturing Requirement Effect

The minimal remanufacturing requirement forces the system to integrate remanufacturing into its activities, modifying the inventory policy. Nevertheless, the quantity remanufactured is only the minimum.

A minimal remanufacturing strategy is easily applied, but the cost (Figure 3.14) associated with this policy is higher than that of another environmental mechanism namely, direct-cap or emission trading. The former strategy reduces the number of possible emissions almost to the maximum keeping a service level in all scenarios of 99%. The standard deviation between the emissions generated in each scenario is approximately 129 units in all scenarios. Meanwhile, in a direct-cap approach when there is a cap of 910t$CO_2$, the standard deviation reaches 3.23 units. Hence, given the different strategies' costs, it is economically advantageous to the company to integrate the cap-and-trade scheme, where the company can have a financial benefit from accounting for and reducing its emissions. Then according to the emission-cap and the allowance price, the inventory policy might help to reduce the quantity of emission while still reducing the cost.

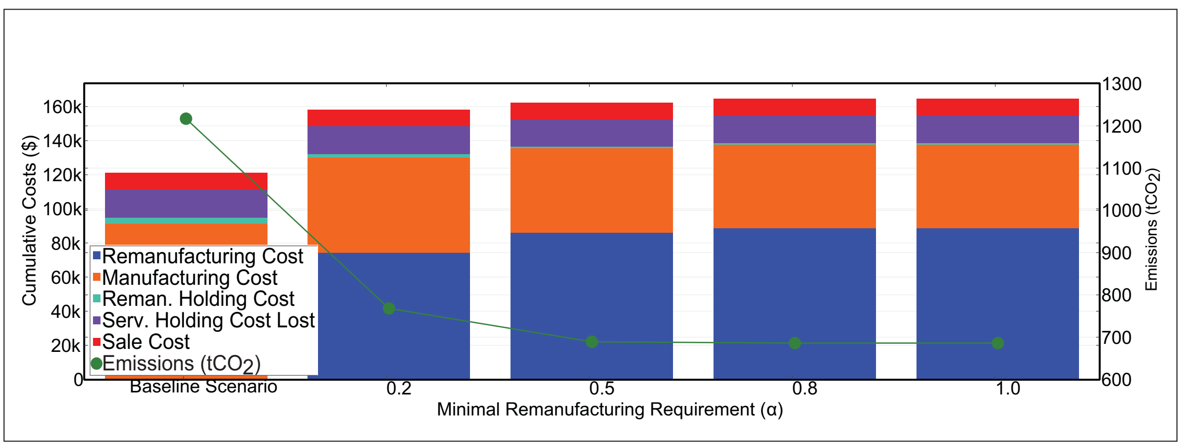


Figure 3.14 Minimal remanufacturing requirement analysis

### 3.7 Conclusions and Future Research

In this paper, we present one of the first finite-horizon inventory systems with recovery and environmental considerations. This paper helps in the understanding of alternative emission control policies and their impact on replenishment decisions. Several conclusions can be drawn from this research study. First, the results indicate that the environmental policies and their factors influence how replenishment decisions are made. In the case that an emission trading scheme is adopted, the allowance price acts as an incentive to implement greener manufacturing processes. This leads to a more significant carbon footprint reduction and an increased profit when allowances are sold. On the other hand, when a direct-cap is preferred, replenishment decisions are made to meet only the minimal carbon footprint requirements. Second, a change on replenishment decisions can achieve a significant reduction in the carbon footprint without highly increasing the cost. This shows that inventory control gives the company flexibility to balance their production processes in order to meet demand, minimize costs, and comply with environmental policies. Third, although replenishment decisions help in the pursuit of carbon abatement; there is a point where these are not sufficient to meet environmental targets without compromising the service level. Hence, when environmental policies are very restrictive, parallel emission-reduction activities as low-carbon technology investments must be implemented.

The present study can take a number of future research directions. This work provides strong evidence that replenishment decisions vary according to the degree of permutation of the allowance price. Then, this analysis could be extended to a scenario reflecting the dynamics of allowance auction. In such a system, the carbon price and the available quantity to purchase are uncertain and vary per period.

This study might be a source of motivation for companies that are still not considering carbon abatement as a competitive advantage. Companies might benefit from advertising a green business and might benefit from an expanded market. Hence, for further research it would also be worthwhile to consider a maximization problem where demand and returns are increased by the environmental implication of the company. This means that demand and returns will be a function of the carbon footprint of the organization. The latter can also be interpreted as a multi-item problem, whereby various markets exist. A market with clients willing to pay more for greener products, and a conventional market, where decisions are based only on product price.

## CHAPTER 4

## ENVIRONMENTAL SUSTAINABILITY FOR LONG-TERM SUPPLY CHAIN DECISIONS UNDER CAP-AND-TRADE REGULATION

Marthy García Alvarado[1], Marc Paquet[1], Amin Chaabane[1]

[1] Department of automated manufacturing engineering, École de technologie supérieure,

1100 Notre-Dame Ouest, Montreal, Quebec, Canada H3C 1K3

Paper submitted to International Journal of Production Economics in February 2016.

**Abstract**

This paper explores how carbon abatement investments, capacity expansion and production and inventory planning interact to comply with environmental legislation. To this end, we consider a single-product supply chain system subject to a cap-and-trade regulation and potential investments. Demand may be met by two production technologies (low-carbon and conventional). The former uses recovered products, and is considered greener, but highly expensive. Further, the capacity of the low-emission process can be increased throughout the planning horizon. Decisions are then made on how to invest in carbon abatement strategies, capacity sizing, and production and carbon management planning to meet a cap-and-trade scheme over time. The aim of this paper is to determine the circumstances under which capacity expansion, strategic investments, such as the treatment of byproducts, and production-inventory planning, help satisfy the new environmental constraints without significantly reducing total profit. We modeled the system as a mixed integer linear problem. To illustrate the applicability of our approach, we focused on the pulp and paper industry. We characterized strategic and tactical decisions and performed a sensitivity analysis to determine the importance of allowance prices and freely granted emissions. Our findings support the potential of aligned strategic and tactical plans under environmental policies. Moreover, our results illustrate that if the allowance price is beyond a threshold price, investments become critical to the economic survival of a firm.

clicours.com

**Keywords:** production planning and inventory control, sustainable supply chain, emission-trading, pulp and paper industry

### 4.1 Introduction

In 2013, California introduced the cap-and-trade system, an environmental policy that promotes the reduction of greenhouse gas (GHG) emissions. Under this program, regulated companies must hold enough carbon credits (allowances) to cover their GHG emissions. It applies to many sectors, such as energy, cement, chemical, glass and paper mills. The program scope increases yearly, and as of 2015, included several industries and countries. Adopting a step toward sustainable development is a long-term plan in which decisions must be made cautiously in order to realize competitive advantages (Crum et al., 2011; Dong et al., 2014).

The impact of the cap-and-trade legislation on a company depends on a broad range of factors, such as demand, energy consumption and the ability to reduce GHG emissions. To comply with the law, companies may reduce their emissions or sell and buy emission allowances through the carbon market. The choice depends on the allowance price and the cost of reducing one metric ton of carbon equivalent ($tCO_2e$). The performance of the cap-and-trade program relies strongly on the carbon market force to drive the allowance price. The notion of prices being set as a function of the supply and demand has a high potential to create competitive advantages for companies that can reduce emissions in a cost-effective manner. However, if decisions made by the companies are not aligned with the law, then their profitability could be jeopardized. The policy is expected to become more rigorous with each passing year, as allowances become more expensive, and their availability reduced. This situation spawns numerous challenges for covered entities. Hence, the mandatory nature of the policy and the imminent tightening of legislation make it imperative to address the integration of cap-and-trade in industries.

Prevailing management methods were initially conceived with purely economic goals, setting aside the environmental impact of decisions. According to the findings of García-Alvarado et al. (2015), existing management strategies cannot successfully lead to a curbing of carbon emissions without sacrificing profit. Nevertheless, changes to production plans and inventory strategies could yield important GHG savings without significant cost increases.

Clearly, there are limits to the ability of tactical decisions to help achieve environmental gains (García-Alvarado et al., 2015). As the allowance prices rise, and the emission-cap tightens, the system struggles to reduce the carbon footprint, and sales are lost. García-Alvarado et al. (2015) stress the need to focus on strategic and tactical decisions to build supply chains that are both cost-effective and environmentally-friendly. Motivated by this, this paper aims to study how strategic (long-term) and tactical decisions interact to ensure compliance with the California Cap-and-Trade Program. Our main interest is to determine the circumstances under which capacity expansion, strategic investments, such as the treatment of byproducts, and production-inventory planning, help satisfy the new environmental constraints without significantly reducing total profit. Further, we believe decision-making under such a mechanism might depend on several factors, namely, the availability of carbon allowances, and their prices. We then study how decisions change when certain critical parameters are perturbed.

The paper is organized as follows. In Section 4.2, we review the literature on strategic and tactical decision-making in terms of sustainable development. In Section 4.3, we present the proposed model. We illustrate the applicability of our model in Section 4.4. Results and findings are discussed in Section 4.5, and conclusions are drawn in Section 4.6.

## 4.2 Cap-and-trade regulation and literature review

In this section, we discuss the California Cap-and-Trade Program in greater detail, including the covered sectors, and we review the most relevant studies for our work.

### 4.2.1 California's cap-and-trade

California's cap-and-trade legislation is intended to control the amount of emissions generated. It focuses on entities generating more than 25,000 $tCO_2e$ yearly. Each year, these entities are required to submit an allowance for each $tCO_2e$ generated, and to that end, companies may buy or sell allowances during auctions.

The cap-and-trade program comprises three compliance periods 1) 2013-2014, 2) 2015-2017, and 3) 2018-2020. The key dynamics of the system during compliance periods are summarized as follows: At the beginning of each year, depending on the sector, the government allocates free emission allowances (emission-cap) to covered facilities. By the end of the year, companies must cover a minimum quantity of their previous year's emissions. Nevertheless, at the end of the compliance period (three years), the total amount of allowances not covered has to be surrendered.

Companies that have exceeded their emission-cap or that have surplus allowances may buy, sell or trade allowances to comply with the legislation. Emissions can be purchased or sold on the carbon market during auctions held at quarterly intervals. During auctions, participants submit bids for allowances in multiples of 1000. There is a maximum quantity of allowances a buyer can purchase per auction. The price paid by bidders is mainly market-driven, although the government also sets a floor allowance price. The floor price is set to increase by 5% per annum, plus the inflation rate. Allowances can likewise be bought in advance for future periods. The purchase limit depends on the auction year.

Companies can bank allowances. Each covered entity possesses two types of accounts for saving their allowances, namely, a compliance account and a holding account. The former holds the allowances needed to comply with the program requirements. At the end of each period (year), the compliance account must hold enough carbon permits to cover the emissions required. Allowances held in this account cannot be transferred elsewhere. In contrast, the holding account permits companies to bank their allowances, which they can then sell or trade. However, there is a limit in the quantity to be held in this account for each compliance period and year.

Figure 4.1 illustrates the dynamics of California's cap-and-trade system. The legislation is projected to become more rigorous with each passing year, while the emission-cap shrinks, and the allowance price rises. Further, each year, the government is expected to expand the scope of the program to include not simply more business sectors, but also other states and countries. For more details on the regulation, we refer the reader to the electronic version issued by the California Air Resources Board (2014).

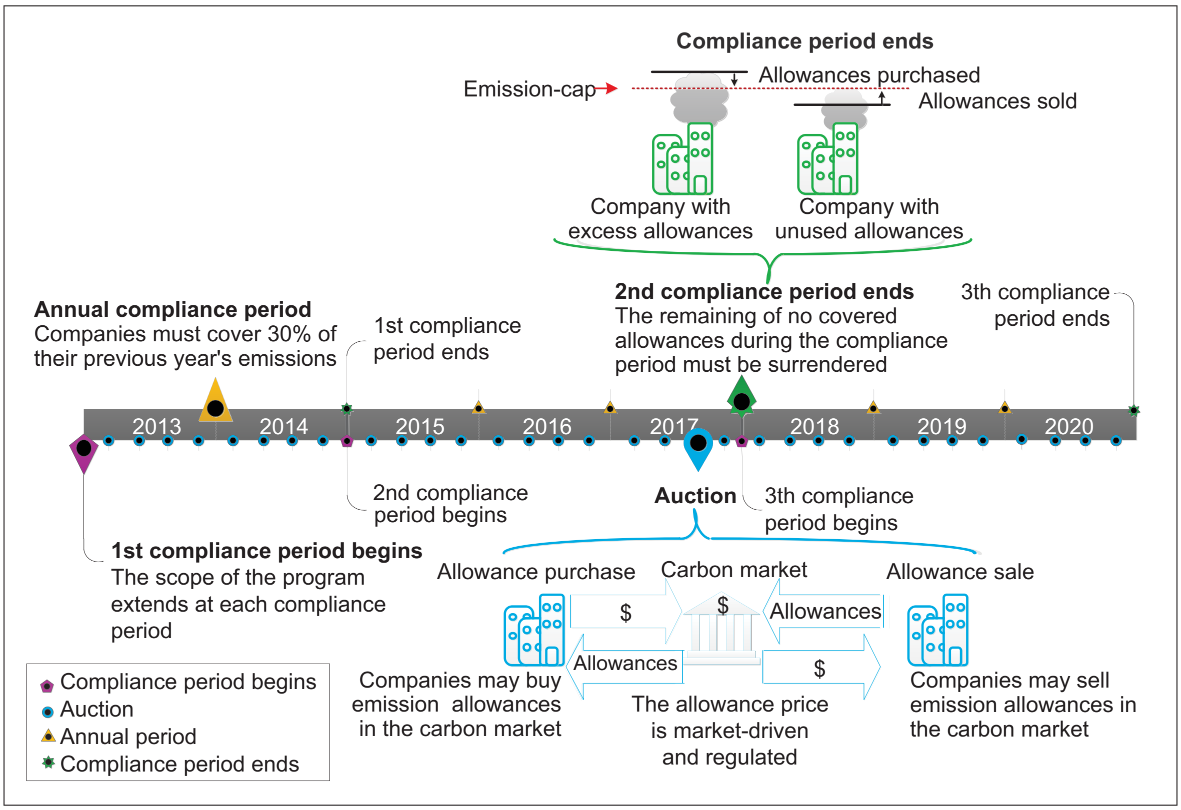


Figure 4.1 Dynamics of California's cap-and-trade system

### 4.2.2 The industrial context

The annual allocation of free allowances relies mostly on the industry's leakage risk and on the sector. It is therefore clear that the cap-and-trade program's effect on profit and decisions will vary from one sector to another. Moreover, because several parameters are estimated at the sector level, and only a few at the facility level, it is hard to predict the long-term effect of the policy at each facility.

The California ARB (Air Resources Board) classifies industries covered by the cap-and-trade scheme in three groups according to leakage risk: 1) high, 2) medium, and 3) low. High risk companies include chemical, cement and paper mills. The medium risk level includes food, winery, and hardware manufacturing sectors, while, the low risk class consists of pharmaceuticals, aircraft manufacturers, etc. (California Air Resources Board, 2014).

The leakage risk determines the assistance factor, which is the fraction of allowances freely granted by the government to support industries. The assistance factor may also be interpreted as an emission-cap which restricts the number of GHG emissions generated by companies. Other factors, such as the cap adjustment and the emission efficiency benchmark, depend on the sector, not in the leakage risk. The cap adjustment factor indicates the tightening of the emission-cap. In most cases, this value represents an annual average 2% reduction. The emission efficiency benchmark is used to evaluate GHG emission efficiency between and among processes in the same industrial sector. The only parameter used at the facility level to calculate the emission-cap is the product output or energy consumed.

The supply chain for each sector and firm is different, which therefore makes it difficult to assess the effect of the regulation on each structure. While there are sectors/companies for which reducing emissions is cheaper and easy, for others, such reductions are more expensive, forcing them to use the carbon market. For example, the paper industry, a high leakage industry, has a wide range of products, some of which can be produced through different technologies and from distinct raw materials. Paper mills using greener technologies would benefit from carbon abatement schemes, while less carbon-efficient competitors would pay for allowances.

### 4.2.3 Related literature

With the introduction of the cap-and-trade scheme system to lower GHG emissions, the literature in the field of supply chains subject to environmental policies has grown significantly. Our work is related to two streams of the literature subject to environmental constraints, namely, environmental investments and production planning and inventory control.

Mondschein and Schilkrut (1997) explored the role of environmental investments. The authors developed a decision support system for investments in pollution abatement plants, facility' sizes and production levels. Later, their work was extended by Caldentey and Mondschein (2003) to incorporate the behavior of the sulfuric acid market. Subramanian et al. (2007) studied investment strategies under emission trading. They found that the number of available permits affects emission abatement levels. Wang et al. (2011) considered environmentally-conscious investments in the design of a supply chain network. The authors showed that larger network capacities led to lesser carbon footprints and costs. Giarola et al. (2012a) studied the selection of technologies in a multi-period supply chain subject to emission trading. They claim that carbon trading may play a fundamental role in promoting more sustainable second-generation technologies. Wang et al. (2013) studied a model for capacity investments with a portfolio of technologies differing in cost and environmental performance subject to emission taxes. Drake et al. (2015) considered a technology choice and capacity investment problem under a cap-and-trade scheme for a single-period make-to-order context. They compared their results with an emission tax policy. Their results support the view that the cap-and-trade system leads to greater profits than does the tax approach. Moreover, high taxes will decrease investments in cleaner technology. More recently, Rezaee et al. (2015) studied a supply chain network design problem subject to the emission-trading scheme. They incorporated uncertainty in carbon prices and argued that the resulting configuration is highly sensitive to the probability distribution of carbon prices.

The study of Gong and Zhou (2013) focus on production planning and inventory control. The authors presented a multi-period production planning subject to a cap-and-trade scheme, and gave insights into the characterization of the optimal production and trading policies. Their results show that policies depend on more states and are not as simple as traditional policies. García-Alvarado et al. (2014) also characterized the inventory policies and the emission trading strategy. The authors studied an infinite-horizon inventory system subject to the cap-and-trade mechanism. Their findings coincide with those of Gong and Zhou (2013). Zhang and Xu (2013) studied a single-period, multi-item production planning subject to a cap-and-trade mechanism. The work of Fahimnia et al. (2015a) focused on how carbon and fuel pricing affects economic and environmental objectives. Their findings show that there is a carbon pricing interval at which the maximum carbon abatement can be achieved without substantial impacts on cost. Later, Fahimnia et al. (2015b) characterized production and allocation strategies for a carbon tax scheme. Zakeri et al. (2015) presented a supply chain planning model subject to carbon tax and emission trading. They argued that although the emission trading scheme is a function of the uncertainty of the carbon market, the supply chain performance in terms of carbon footprint, cost, and service level is superior to the situation in a carbon tax context. García-Alvarado et al. (2015) studied the effect of a cap-and-trade scheme on replenishment decisions relating to a hybrid supply chain system over a finite horizon. They provided evidence of a threshold emission-cap value under which strategic investments, rather than tactical decisions, must be made.

The literature examining strategic and tactical decisions in the presence of environmental concerns, includes the work of Chaabane et al. (2012), who studied a supply chain network subject to a cap-and-trade scheme. Their results support the position that carbon management strategies aid in achieving sustainability targets. Jiang and Klabjan (2012) studied joint production and environmental investment decisions under several carbon regulations with uncertain demand. Their findings indicate the environmental policies and system' characteristics under which investments will be made. The study by Krass et al. (2013) focused on the effect of using tax, subsidies and rebate level as motivation for emission abatement technologies and production levels. As does the work of Drake et al. (2015), their findings show that higher taxes induce dirtier technologies. Dong et al. (2014) focused on a centralized two-echelon single-period system with demand subject to sustainability investments in products and a cap-and-trade mechanism. The authors determine the optimal production quantity and sustainability initiatives, and affirm that profit can be increased when environmental investments are made.

Even though the literature examined several aspects of the cap-and-trade scheme no study, to our knowledge, has integrated on production planning and inventory control methods the actual dynamics of the cap-and-trade strategy. Hence, little is known about the potential of incorporating strategic and tactical planning under a carbon management scheme. The aim of this paper is to bridge the gap between what is present in the literature and the cap-and-trade scheme. Further, we explore how environmental investments and capacity sizing maximize profit while minimizing the carbon footprint of a firm.

## 4.3 Problem description and model formulation

### 4.3.1 Problem description

The system under study is illustrated in Figure 4.2. We considered a finite-horizon single-product supply chain subject to a cap-and-trade scheme. The system consists of a manufacturing and a remanufacturing production facility. The production capacity of the remanufacturing facility can be increased over time. It also has three stocking points; one for recovered products, a second for virgin raw material, and a third for serviceable items. We assume that the production facilities and stocking points are already established. Therefore, the main decisions to be made are at the strategic level, which includes environmental project investments, capacity sizing, sales, and production/inventory planning; decisions will also be made at the tactical level, which will cover carbon management strategies.

The planning horizon is composed of a set $\mathscr{M}$ of annual compliance periods defined by $m = 1,...,M$. Annual compliance periods are classified as initial, closing and regular periods. Initial periods establish the beginning of a three-year compliance period. Closing periods denote the end of three-year periods, and regular periods refer to the periods comprised in a three-year interval. We define the set of closing periods as $\mathscr{J} \subset \mathscr{M}$. The number of allowances to surrender changes depending on whether the period is the beginning, the end, or a regular year of a compliance period.

Under the cap-and-trade scheme studied, at the beginning of each year (compliance period) $m \in \mathscr{M}$, an amount $\alpha_m$ of allowances is freely granted to the system (emission-cap). This quantity

Clicours.COM

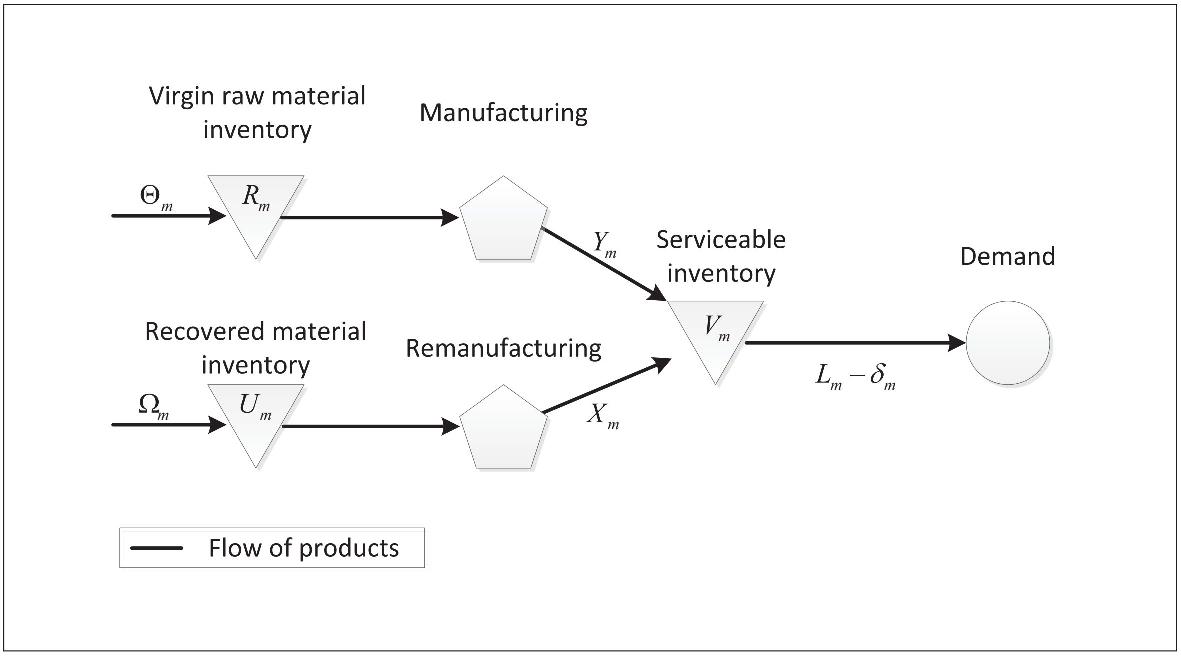


Figure 4.2  Flow of products in the system under study

is reduced each year by a factor $\varepsilon_m$. During regular annual periods $m \in \mathcal{M} \setminus \mathcal{J}$, a minimal percentage ($\tau_m$) of the previous year's emissions has to be covered with allowances. During closing compliance periods $j = 1, ..., J$, there is no yearly obligation, but rather, a triennial obligation. The sum of uncovered emissions during the years of the compliance period must then be surrendered. The compliance account level ($C_m$) must be positive for all annual periods and hold the amount of emissions required for each year. If a company exceeds the freely allocated emissions or has an allowance surplus, carbon allowances can be bought and sold during auction periods held quarterly each year.

We defined a set $\mathcal{N}$ of auction periods $n = 1, ..., N$ distributed quarterly each year. Each year $m \in \mathcal{M}$, during each auction period $n \in \mathcal{N}$, it is possible to purchase $(B_{m,n,m'})$ or sell emissions $(S_{m,n})$ on the carbon market at price $b_{m,n}$ and $s_{m,n}$, respectively. To ensure the problem is bounded, we assume $s_{m,n} < b_{m,n}$ during all compliance periods. Allowances must be bought in multiples of 1000, and there is an allowance purchase limit ($g_{m,n}$) during each auction. We assume the sale of excess allowances is also made in batches of 1000 and is bounded by a maximum sale quantity ($g_{m,n}$). Carbon allowances can be banked at the holding account $(H_m)$

from period to period as long as the holding limit $(h_m)$ is not surpassed. The flow of emissions is summarized in Figure 4.3.

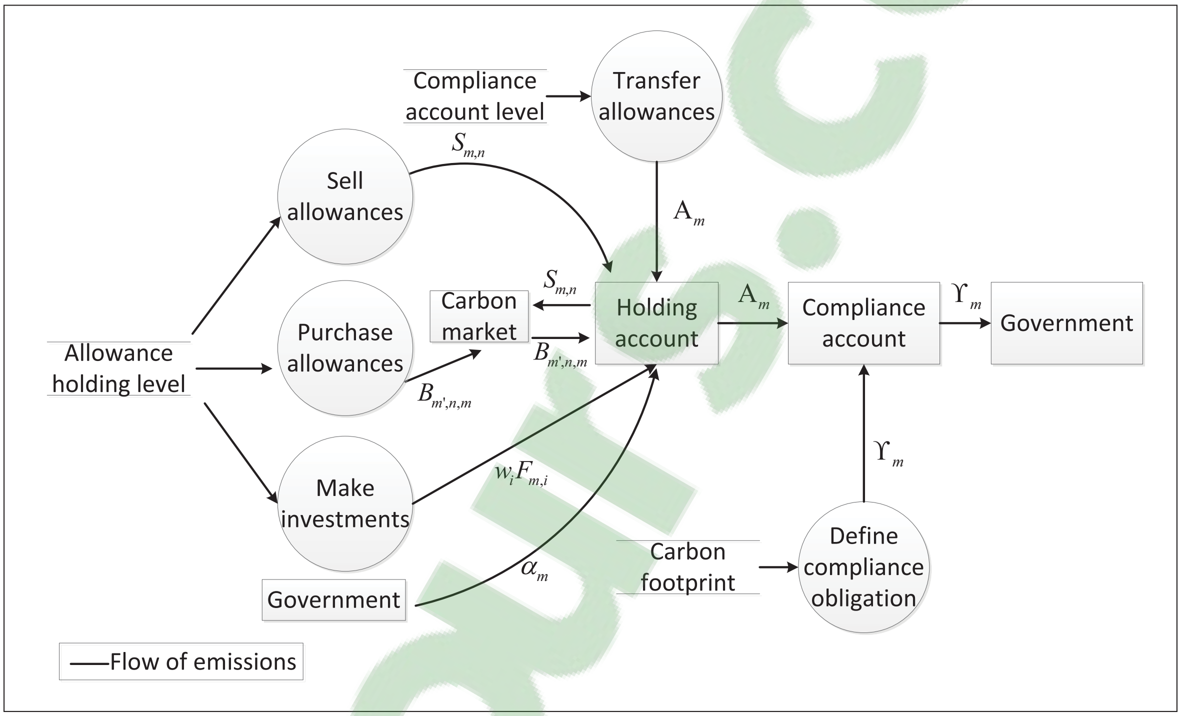


Figure 4.3    Flow of emissions in the system under study

We considered annual demand $(\delta_m)$ as independent random variables. Demand can be satisfied by two processes, namely, manufacturing and remanufacturing. Both technologies have an environmental impact denoted by $e$ $(q)$ and a cost $y$ $(x)$ per unit, respectively. We assumed $q < e$ and $y > x$. Remanufacturing orders $(Y_m)$ require recovered materials. Returns $(\Omega_m)$ are held in the remanufacturable stocking point $(Z_m)$, and there is a holding cost $(\mu)$ associated with the average inventory level during each period. We considered the quality of end-of-life products to be stable, and that there is a market surplus. Therefore, we assumed the acquisition of recovered products to be deterministic. Meanwhile, manufacturing orders $(X_m)$ require virgin raw material $(\Theta_m)$. Virgin material is held in the stocking point $R_m$, and at the end of periods, the average inventory level incurs a holding cost $\sigma$. Both technologies manufacture the same quality of products. Replenishment orders arrive with zero lead-time at the serviceable stocking point ($V_m$), where a holding cost ($\gamma$) is incurred by the average inventory level during each period. Demand is satisfied from the serviceable inventory.

To reduce the carbon footprint, the remanufacturing capacity can be expanded by $J_m$ increments at a variable cost $\kappa$ and a fixed cost $d$. However, capacity cannot exceed a given maximum $\bar{k}$. It is also possible to gain allowances (environmental rewards) by making investments in emission abatement technology. We assumed as emissions are cut, carbon abatement technology will require major investments to activate more emission reductions. Hence, we considered the environmental reward to be a piecewise linear function of the investments made ($F_{m,i}$). We defined a set of segments $\mathscr{I}$ with $i = 1,...,I$. The length of each segment is given by $\varsigma_i$, and its environmental reward is denoted by $w_i$, as illustrated in Figure 4.4.

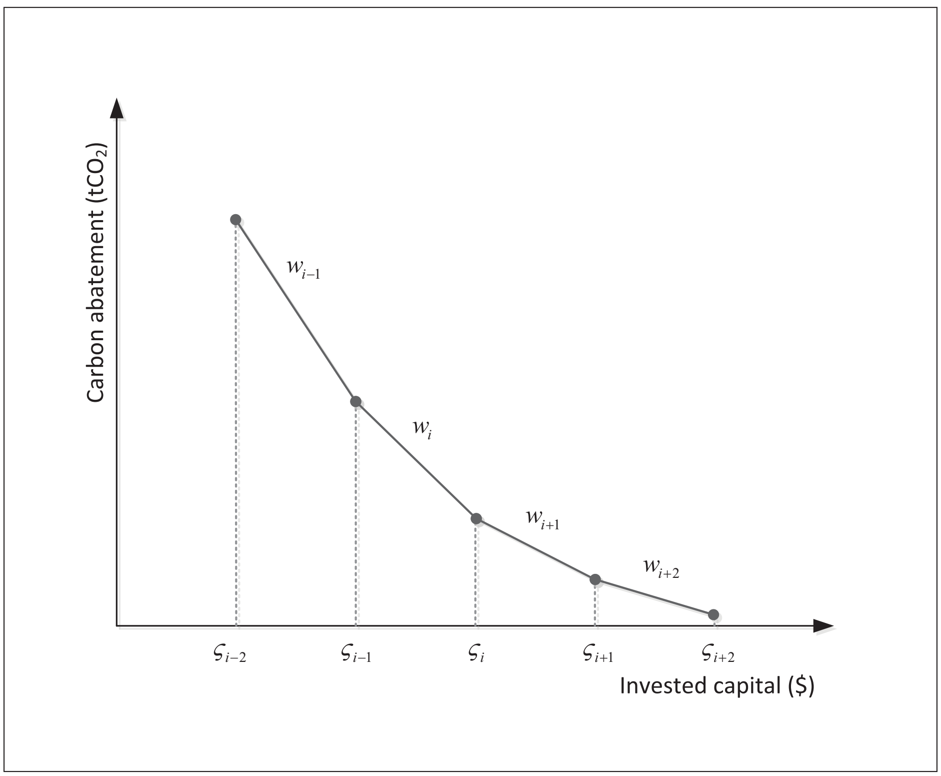


Figure 4.4 Environmental piecewise linear function

### 4.3.2 Sequence of decisions

Events proceed according to the following sequence: At the beginning of each compliance period $m \in \mathscr{M}$, remanufacturing capacity expansion, and environmental project investments $i \in \mathscr{I}$ are reviewed and carried out, if applicable. The benefits of capacity expansion and project investment are seen immediately during period $m \in \mathscr{M}$. Likewise, at the beginning of annual compliance periods, inventory levels are reviewed, and raw material, manufacturing, and remanufacturing orders are placed. Afterward, demand occurs. Sales are made based on the available serviceable inventory. We assume that all costs and cash flows arrive at the end of the period. At the beginning of each auction period, the emission bank is reviewed and the number of allowances to purchase or to sell is determined. Allowance buying and selling occur instantly. The objective is to determine the optimal capacity expansion, environmental technology investments, carbon strategy, and production and sales quantities to maximize the total profit over the planning horizon.

To formulate the problem, the notation of this paper is summarized as follows:

**Sets**

| | |
|---|---|
| $\mathscr{M}$: | Annual compliance periods. |
| $\mathscr{J} \subset \mathscr{M}$: | Closing years of compliance periods. |
| $\mathscr{N}$: | Auction periods. |
| $\mathscr{I}$: | Segments of the investment piecewise linear function. |

**Decision Variables**

$B_{m,n,m'}$: Amount of allowances bought (in multiples of 1,000) during period $m \in \mathscr{M}$ and auction $n \in \mathscr{N}$ and to be used during period $m' \in \mathscr{M}$ s.t. $m' \geq m$.

$S_{m,n}$: Amount of allowances sold (in multiples of 1,000) during auction $n \in \mathscr{N}$ and period $m \in \mathscr{M}$.

$\Delta_m$: Carbon footprint of period $m \in \mathscr{M}$.

$\Upsilon_m$ Quantity of allowances surrendered at the beginning of period $m \in \mathscr{M}$.

$\Lambda_m$: Allowances transferred to the compliance account at the beginning of period $m \in \mathscr{M}$.

$C_m$: Compliance account level at the beginning of period $m \in \mathscr{M}$.

$\alpha_m$: Allowances freely allocated at period $m \in \mathscr{M}$.

$H_m$: Holding account level at period $m \in \mathscr{M}$.

$V_m$: Serviceable inventory level at the end of period $m \in \mathscr{M}$.

$Z_m$: Remanufacturable inventory level at the end of period $m \in \mathscr{M}$.

$R_m$: Virgin raw material inventory level at the end of period $m \in \mathscr{M}$.

$Y_m$: Quantity manufactured during period $m \in \mathscr{M}$.

$X_m$: Quantity remanufactured during period $m \in \mathscr{M}$.

$\Pi_i$: 1 if abatement rate $i \in \mathscr{I}$ is used; 0 otherwise.

$F_{m,i}$: Investment made at rate $i \in \mathscr{I}$ during period $m \in \mathscr{M}$.

$K_m$: Capacity of remanufacturing during period $m \in \mathscr{M}$.

$J_m$: Remanufacturing capacity expansion during period $m \in \mathscr{M}$.

$D_m$: 1 if remanufacturing capacity is expanded during period $m \in \mathscr{M}$; 0 otherwise.

$L_m$: Lost sales during period $m \in \mathscr{M}$.

$\Theta_m$: Virgin material required during period $m \in \mathscr{M}$.

$\Omega_m$: Recovered material required during period $m \in \mathscr{M}$.

$A$: Total carbon footprint over the whole planning horizon.

$\psi$: Fill rate.

**Environmental parameters**

$b_{m,n}$: Allowance purchase price (per allowance batch)
during period $m \in \mathscr{M}$ and auction $n \in \mathscr{N}$.

$s_{m,n}$: Allowance selling price (per allowance batch)
during period $m \in \mathscr{M}$ and auction $n \in \mathscr{N}$.

$g_{m,m'}$: Maximal purchase/sale limit (in allowance batches) during period $m \in \mathscr{M}$ for period $m' \in \mathscr{M}$.

$\tau_m$: Minimal percent to surrender of required allowances during period $m \in \mathscr{M}$.

$w_i$: Carbon reduction rate at $i \in \mathscr{I}$.

$\varepsilon_m$: Cap adjustment factor during period $m \in \mathscr{M}$.

$\beta_m$: Industry assistance factor during period $m \in \mathscr{M}$.

$e$: Carbon emissions per unit manufactured.

$q$: Carbon emissions per unit remanufactured.

$\bar{e}$: Carbon emissions benchmark per ton produced.

$h_m$: Holding limit at period $m \in \mathscr{M}$.

$o_m$: Initial period for compliance period ending during year $m \in \mathscr{J}$.

$\bar{c}$: Final compliance account level.

$\bar{h}$: Final holding account level.

$\bar{g}$: Allowance batch size (1,000 allowances).

**Parameters: costs and revenues**

$p$: Retail price per unit

$\nu$: Lost sale price per unit

$\gamma$: Inventory holding cost per unit hold at the serviceable inventory.

$\mu$: Inventory holding cost per unit hold at the remanufacturable inventory.

$\sigma$: Inventory holding cost per unit hold at the raw material inventory.

$y$: Production cost per ton manufactured.

$x$: Production cost per ton remanufactured.

$\theta$: Acquisition cost per unit of virgin raw material.

$\omega$: Acquisition cost per unit of recovered material.

$d$: Fixed cost of remanufacturing capacity expansion.

$\kappa$: Variable cost of remanufacturing capacity expansion.

$\varsigma_i$: Length of segment $i \in \mathscr{I}$ .

**Other parameters and capacities**

$\bar{k}$ Maximal remanufacturing capacity.

$\lambda$ Capacity of manufacturing.

$v$ Capacity of serviceable inventory.

$u$ Capacity of remanufacturable inventory.

$r$ Capacity of virgin raw material inventory.

$\bar{v}$ Final serviceable inventory.

$\bar{u}$ Final remanufacturable inventory.

$\bar{r}$ Final virgin raw material inventory.

$\delta_m$ Customer demand during period $m \in \mathcal{M}$.

$k$ Discount rate.

### 4.3.3 Objective function

The objective function (4.1) to be maximized is the net present value. It consists of 1) sales revenue; 2) emission trading revenue; 3) emission trading cost; 4) investment cost; 5) capacity expansion cost; 6) raw material acquisition cost; 7) production cost, and 8) inventory holding cost:

$$
\begin{aligned}
\max\ & \underbrace{\sum_{m\in\mathcal{M}} \left(\frac{1}{1+k}\right)^m \left(p\left(\delta_m - L_m\right) - \nu L_m\right)}_{\text{sales revenue}} + \underbrace{\sum_{n\in\mathcal{N}} \sum_{m\in\mathcal{M}} \left(\frac{1}{1+k}\right)^m \left(s_{m,n} S_{m,n}\right)}_{\text{emission trading revenue}} \\
& - \underbrace{\sum_{n\in\mathcal{N}} \sum_{m\in\mathcal{M}} \sum_{m'\in\mathcal{M}} \left(\frac{1}{1+k}\right)^m \left(b_{m,n} B_{m,n,m'}\right)}_{\text{emission trading cost}} - \underbrace{\sum_{m\in\mathcal{M}} \sum_{i\in\mathcal{I}} \left(\frac{1}{1+k}\right)^m F_{m,i}}_{\text{investment cost}} \\
& - \underbrace{\sum_{m\in\mathcal{M}} \left(dD_m + \kappa J_m\right)}_{\text{capacity expansion}} - \underbrace{\sum_{m\in\mathcal{M}} \left(\frac{1}{1+k}\right)^m \left(\theta\Theta_m + \omega\Omega_m\right)}_{\text{raw material acquisition cost}} \\
& - \underbrace{\sum_{m\in\mathcal{M}} \left(\frac{1}{1+k}\right)^m \left(yY_m + xX_m\right)}_{\text{production cost}} - \underbrace{\sum_{m\in\mathcal{M}} \left(\frac{1}{1+k}\right)^m \left(\gamma\bar{V}_m + \mu\bar{U}_m + \sigma\bar{R}_m\right)}_{\text{inventory holding cost}}
\end{aligned}
\tag{4.1}
$$

### 4.3.4 Constraints

The above function is subject to the following set of constraints 1) environmental; 2) investment; 3) inventory balance; 4) capacity; and 5) non-negativity and integrity.

#### 4.3.4.1 Environmental constraints

The number of allowances freely granted to the system is given by Expression (4.2). The quantity of carbon permits conferred is a function of the production quantities, benchmark carbon footprints, the assistance factor, and the yearly cap adjustment.

$$\beta_m \varepsilon_m \bar{e}\left(Y_{m-2} + X_{m-2}\right) \geq \alpha_m \qquad \forall m \in \mathscr{M} \quad (4.2)$$

The carbon footprint at each period, Expression (4.3), is calculated as a function of the carbon emissions generated by the quantities produced.

$$\Delta_m = eY_m + qX_m \qquad \forall m \in \mathscr{M} \quad (4.3)$$

Covered entities must respect their annual compliance obligation. The quantity of allowances that must be surrendered at the end of each period must be greater than or equal to a minimal requirement given by Expression (4.4). We assume by constraint (4.5) that the quantity to surrender cannot exceed the previous year's emissions.

$$\Upsilon_m \geq \tau_m \Delta_{m-1} \qquad \forall m \in \mathscr{M} \setminus \mathscr{J} \quad (4.4)$$

$$\Upsilon_m \leq \Delta_{m-1} \qquad \forall m \in \mathscr{M} \setminus \mathscr{J} \quad (4.5)$$

For closing compliance periods, the triennial compliance obligation must be respected. The number of allowances to submit is the sum of the non-surrendered allowances during the three-year period.

$$\Upsilon_m = \sum_{\substack{l \in \mathscr{M} \\ o_m \leq l \leq m-1}} \Delta_l - \sum_{\substack{l \in \mathscr{M} \\ o_m+1 \leq l \leq m-1}} \Upsilon_l \qquad \forall m \in \mathscr{J} \quad (4.6)$$

To take account of the emissions generated at the end of the horizon, we add the emissions generated during period $M$ to the triennial compliance obligation during period $M$.

$$\Upsilon_M = \sum_{\substack{l \in \mathscr{M} \\ o_M \leq l \leq M}} \Delta_l - \sum_{\substack{l \in \mathscr{M} \\ o_M+1 \leq l \leq M-1}} \Upsilon_l \qquad \forall m \in \mathscr{J} \quad (4.7)$$

The balance of the compliance account is equal to the number of allowances from the previous period plus the quantity of allowances transferred to the account minus the number of allowances surrendered.

$$C_m = C_{m-1} + \Lambda_m - \Upsilon_m \qquad \forall m \in \mathscr{M} \quad (4.8)$$

Constraint (4.9) expresses the allowance holding balance. The number of allowances held during each period $m \in \mathscr{M}$ is given by the sum of the emissions granted to the system at the beginning of the period; the emissions from the previous year; the environmental benefit of investments, and the amount of allowances purchased, minus the allowances sold.

$$H_m = \alpha_m + H_{m-1} - \Lambda_m + \sum_{i \in \mathscr{I}} w_i F_{m,i} - \sum_{n \in \mathscr{N}} \bar{g} S_{n,m} + \sum_{n \in \mathscr{N}} \sum_{\substack{m' \in \mathscr{M} \\ m' \leq m}} \bar{g} B_{m',n,m} \qquad \forall m \in \mathscr{M} \quad (4.9)$$

There is a limit on allowance holding defined by constraint (4.10), and according to it, the amount of allowances banked at each period must be less than or equal to the maximum allowance holding.

$$H_m \leq h_m \qquad \forall m \in \mathscr{M} \quad (4.10)$$

The amount of allowances purchased cannot exceed a given maximum quantity.

$$B_{m,n,m'} \leq g_{m,m'} \qquad \forall m, m' \in \mathscr{M}, \forall n \in \mathscr{N} \quad (4.11)$$

To avoid emptying the system, a minimal number of allowances must be held at the end of the horizon.

$$C_M \geq \bar{c} \tag{4.12}$$

$$H_M \geq \bar{h} \tag{4.13}$$

#### 4.3.4.2 Investment constraints

Conditional constraints for each segment of the investment curve are given by Expressions (4.14) and (4.15).

$$\sum_{m\in\mathscr{M}} F_{m,i} \leq \varsigma_i \Pi_{i-1} \qquad \forall i \in \mathscr{I} \tag{4.14}$$

$$\sum_{m\in\mathscr{M}} F_{m,i} \geq \varsigma_i \Pi_i \qquad \forall i \in \mathscr{I} \tag{4.15}$$

#### 4.3.4.3 Inventory balance constraints

The remanufacturable, virgin raw material and serviceable inventory balances are given by Expressions (4.16) to (4.18), respectively: The stock of virgin material is given by the inventory level during the previous period minus the quantity manufactured, plus the amount of virgin material bought. Likewise, the remanufacturable inventory during each period considers the inventory level at the preceding period, the remanufactured amount, and the quantity of end-of-life products purchased during period $m \in \mathscr{M}$. Meanwhile, the serviceable inventory level is defined by the serviceable inventory level during the previous period, plus the amount produced by both processes, minus the sales.

$$R_m = R_{m-1} - Y_m + \Theta_m \qquad \forall m \in \mathscr{M} \quad (4.16)$$

$$U_m = U_{m-1} - X_m + \Omega_m \qquad \forall m \in \mathscr{M} \quad (4.17)$$

$$V_m = V_{m-1} + Y_m + X_m + L_m - \delta_m \qquad \forall m \in \mathscr{M} \quad (4.18)$$

The average inventory levels for the three stocking points are computed in the following form:

$$\bar{R}_m = \frac{R_{m-1} + R_m}{2} \qquad \forall m \in \mathscr{M} \quad (4.19)$$

$$\bar{U}_m = \frac{U_{m-1} + U_m}{2} \qquad \forall m \in \mathscr{M} \quad (4.20)$$

$$\bar{V}_m = \frac{V_{m-1} + v_m}{2} \qquad \forall m \in \mathscr{M} \quad (4.21)$$

The final inventories must be greater than the minimal requirement.

$$R_M \geq \bar{r} \qquad (4.22)$$

$$U_M \geq \bar{u} \qquad (4.23)$$

$$V_M \geq \bar{v} \qquad (4.24)$$

#### 4.3.4.4 Capacity constraints and upper limits

Expression (4.25) ensures that the remanufacturing capacity at each period depends on the previous period's capacity plus the expansions made previously. Moreover, according to Expression (4.26), the total capacity must not exceed a given maximum level.

$$K_m = K_{m-1} + J_m \qquad \forall m \in \mathscr{M} \quad (4.25)$$

$$K_m \leq \bar{k} \qquad \forall m \in \mathscr{M} \quad (4.26)$$

clicours.com

Expression (4.27) is an auxiliary constraint to consider if an expansion has been made, and a fixed cost is incurred.

$$J_m \leq \bar{k} D_m \qquad \forall m \in \mathscr{M} \quad (4.27)$$

Process capacities are defined by Expressions (4.28)-(4.29); according to these, the amount fabricated for each technology cannot exceed their corresponding production capacity. Similarly, constraints (4.30)-(4.31) ensure that the quantity held in each inventory does not exceed the holding capacity of the respective stocking points.

$$Y_{m,} \leq \lambda \qquad \forall m \in \mathscr{M} \quad (4.28)$$

$$X_m \leq K_m \qquad \forall m \in \mathscr{M} \quad (4.29)$$

$$V_m \leq v \qquad \forall m \in \mathscr{M} \quad (4.30)$$

$$U_m \leq u \qquad \forall m \in \mathscr{M} \quad (4.31)$$

$$R_m \leq r \qquad \forall m \in \mathscr{M} \quad (4.32)$$

Constraint (4.33) expresses upper limits on the amount of lost sales per period; lost sales cannot exceed demand during any period.

$$L_m \leq \delta_m \qquad \forall m \in \mathscr{M} \quad (4.33)$$

#### 4.3.4.5 Non-negativity and integrity constraints

Finally, constraints (4.35) to (4.44) express the non-negativity and, if applicable, the integrity of the decision variables.

$$F_{m,i} \in \mathbb{R}_+, \qquad \forall m \in \mathscr{M}, \quad \forall i \in \mathscr{I} \tag{4.34}$$

$$V_m, Z_m, H_m, L_m, K_m \in \mathbb{R}_+ \qquad \forall m \in \mathscr{M} \tag{4.35}$$

$$\Upsilon_m, \Lambda_m, \Delta_m \in \mathbb{R}_+, \qquad \forall m \in \mathscr{M} \tag{4.36}$$

$$C_m, R_m, \Theta_m, \Omega_m \in \mathbb{R}_+, \qquad \forall m \in \mathscr{M} \tag{4.37}$$

$$\bar{R}_m, \bar{U}_m, \bar{V}_m \in \mathbb{R}_+, \qquad \forall m \in \mathscr{M} \tag{4.38}$$

$$Y_m, X_m \in \mathbb{R}_+, \qquad \forall m \in \mathscr{M} \tag{4.39}$$

$$\alpha_m, J_m \in \mathbb{Z}_+, \qquad \forall m \in \mathscr{M} \tag{4.40}$$

$$B_{m,n,m} \in \mathbb{Z}_+, \qquad \forall m, m' \in \mathscr{M}, \quad \forall n \in \mathscr{N} \tag{4.41}$$

$$S_{m,n} \in \mathbb{Z}_+, \qquad \forall m \in \mathscr{M}, \quad \forall n \in \mathscr{N} \tag{4.42}$$

$$D_m \in \{0,1\}, \qquad \forall m \in \mathscr{M} \tag{4.43}$$

$$\Pi_i \in \{0,1\}, \qquad \forall i \in \mathscr{I} \tag{4.44}$$

#### 4.3.4.6 Other performance indicators

Other performance indicators than profit, such as the total carbon footprint and the fill rate, are required to evaluate the performance of the system. Expression (4.45) gives the carbon footprint.

$$A = \sum_{m \in \mathscr{M}} \Delta_m \tag{4.45}$$

The fill rate ($\psi$) is determined as the proportion of total unfilled demand, given by Expression (4.46).

$$1-\psi=\frac{1}{M}\sum_{m\in\mathscr{M}}\frac{L_m}{\delta_m} \tag{4.46}$$

## 4.4 Illustrative example

We carried out an extensive numerical analysis of several allowance prices and assistance factors. We applied our methodology to the pulp and paper industry. Although our study focuses on the paper sector, it can be applied to any other context as long as the context shares the same characteristics discussed in Section 4.3.

### 4.4.1 Pulp and paper industry

The carbon footprint of the paper industry is significant. Paper production requires a substantial quantity of wood, involves high energy consumption, and generates numerous $CO_2$e emissions. The result is that paper mills are classified as falling under a high leakage industry. The largest paper mills in the world are based in the U.S., Japan, Finland, Sweden and Canada (Martel et al., 2005). Since under California's cap-and-trade scheme, paper mills must compete with unregulated companies, they must study the integration of the emission-cap policy at a deeper level to remain competitive. In this context, the use of waste paper as raw material may help to enhance the achievement of carbon footprint targets.

The system under study is illustrated in Figure 4.5. Our analysis covers production costs and the carbon footprint at the mill level. We focus on integrated manufacturing plants that produce both pulp and paperboard. For instance, we do not take into account transport or elements where emissions are assumed to be negligible. These elements could be the subject of further studies. The production cost includes major expenses, such as raw material and production salaries. On the other hand, carbon emissions are considered from the energy consumed and byproducts. As described in Section 4.3, there are two processes available: Manufacturing, which uses harvest forest as raw material, and remanufacturing, which transforms recovered paper into finished products. Recycled paper used in remanufacturing saves the need to harvest the forest, but at the same time, it involves special processes such as sorting, cleaning, and washing, which require additional energy. Moreover, we assume that facilities using virgin material are larger than recycling facilities, and scale economies are then possible. We thus considered that remanufacturing is greener but more expensive than manufacturing. Regarding environmental investments, a wide range of projects can be realized to reduce the total carbon footprint. These include by-product recovery/treatment, water reuse, equipment upgrade, fuel substitution, etc.

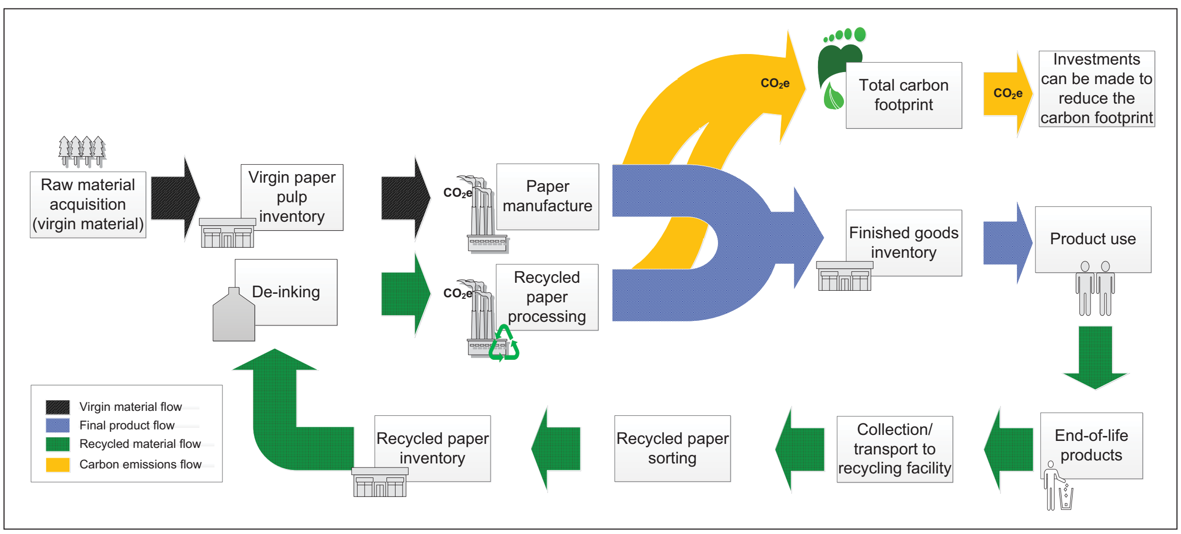


Figure 4.5 Example of a supply chain under study: pulp and paper supply chain

We focused on paper mills in the U.S. and Canada. We utilized data from the United States Environmental Protection Agency (USEPA) and companies' records to characterize paper manufacturing costs and requirements. For carbon footprints, our study relied on official reports of the California ARB. The aim of this work is to provide a set of baseline insights for managers regarding environmental investments and replenishment decisions in the face of environmental constraints.

### 4.4.2 Proposed methodology

The proposed model was written in Pyhton and solved using Gurobi. The experiments were run on an Intel®Core$^{TM}$i7 2.20 GHz PC. The average optimization time was 0.05 s, although we limited the time to 100 s.

Our primary interest is to determine the circumstances under which, strategic investments, and production-inventory planning aid to satisfy the new environmental constraints without significantly sacrificing total profit. Motivated by this, we studied two scenarios:

**Scenario 1- Baseline problem**
The first set of scenarios aims to establish the limitations of tactical planning. To this end, it assumes that investments and capacity expansions are impossible, and we can therefore only take advantage of the carbon market to maximize the long-term wealth of the firm.

**Scenario 2- Carbon abatement strategies**
The second set of scenarios investigates the profitability of making investments in capacity expansion and pollution abatement technologies.

We compared both scenarios and analyzed how decision-making changed and to what extent the optimal value was affected. Obviously, there are certain factors that interact in decision-making. The proposed approach is therefore used to a) determine the importance of investments, capacity sizing, and production and inventory policy in satisfying environmental constraints; b) characterize parameter interactions, and c) define how permuting the different parameter values affects decision-making. To determine the total profit of the system, we used Expression (4.1). Expression (4.45) would be used to determine the carbon footprint of the company. Meanwhile, the fill rate was evaluated through Expression (4.46).

### 4.4.3 Data sources

To characterize the cap-and-trade scheme, we used data reported by the California ARB on the cap-and-trade mechanism.

#### Compliance periods

We studied the compliance periods spanning the 2015-2033 period (19 years). We considered 2015, 2018, 2021, 2024, 2027 and 2030 as initial and closing periods. In 2015, the company had to surrender the emissions from 2013 and 2014. We considered that the company had already submitted 2015 requirements, and that for that year, there are no emissions to surrender. In 2018, the remaining 2015-2017 emissions would be submitted. By 2021, the remaining 2018-2020 emissions would be surrendered, etc.

#### Allowance prices

Based on the floor price of 2015 ($12.10 per allowance), we studied allowance prices in the [$20,$300] range over the whole planning horizon. We assumed an inflation rate of 2% and that there is a loss when allowances are sold.

#### Auction budgets and limits

We took into account only the allowance budget relative to California. Moreover, the number of allowances auctioned corresponds just to the current year's budgets, and there are no allowances from prior years. We considered a 12Mt$CO_2$ (millions of t$CO_2$) allowance budget reduction for undefined years.

Auction limits were set at 25% of the allowances offered at each auction. For advance-years auctions, we assumed 10% of the year's available permits. Purchase limits are estimated as 15% of auctions offered during current years and 25% for advance auctions.

### Annual allocations and compliance requirements

The industry assistance factor for paper manufacturing is 100% regardless of the compliance period. To extend our analysis, we studied assistance factors in the [40%,100%] interval. Moreover, to represent the yearly decrease in free allocation, we used an adjustment factor of 2%. Furthermore, during regular years, at least 30% of the previous year's emissions must be surrendered.

### Other parameters

For paper mills, the benchmark $CO_2$ footprint is 1.31 allowances per ton produced. Final inventory and compliance requirements were set according to average values obtained from a preliminary study. The remaining parameters are summarized in Tables 4.1 and 4.2.

Table 4.1 General parameters

| Parameter | Values | Parameter | Values |
|---|---|---|---|
| **Environmental parameters** | | | |
| Allocation yearly decrease | 2% | Minimal percent to surrender per year | 30% |
| Manufacturing carbon footprint | 4.00 $tCO_2$/ton | Remanufacturing carbon footprint | 1.90 $tCO_2$/ton |
| **Costs and capacities** | | | |
| Profit ($p$) | $900/ton | Lost sale cost ($L$) | $270/ton |
| Discount rate | 2% | Capacity expansion cost | $10/ton |
| Manufacturing cost | $200/ton | Remanufacturing cost | $350/ton |
| Manufacturing capacity | 590,000 tons | Maximal remanufacturing capacity | 590,000 tons |
| Virgin raw material cost | $300/ton | Recovered material cost | $200/ton |
| Virgin holding capacity | 108,000 | Recovered holding capacity | 72,000 tons |
| Holding cost for virgin material | $10/ton | Holding cost for recovered material | $6/ton |
| Finished holding capacity | 180,000 tons | Holding cost for finished material | $180/ton |
| **Demand** | | | |
| Annual demand | $\mathcal{N}$(590,000, 20,000) tons/year | | |

### 4.4.4 Results

In the following sections, we summarize our findings.

Table 4.2 Initial and final bounds

| Parameter | Values | Parameter | Values |
|---|---|---|---|
| **Initial and final bounds** | | | |
| $X_2$ | 0 tons | $X_1$ | 0 tons |
| $Y_2$ | 590,000 tons | $Y_1$ | 590,000 tons |
| Initial inventory level (virgin and recovered material) | 0 tons | Final inventory level (virgin and recovered material) | 0 tons |
| Initial serviceable inventory level | 0 tons | Final serviceable inventory level | 5 700 tons |
| Initial holding level | 0 allowances | Initial compliance level | 0 allowances |
| Final holding level | 1,000 allowances | Final compliance level | 1,000 allowances |

#### 4.4.4.1 Profit, fill rate and carbon footprint

In the model presented in Section 4.3, we measured the carbon footprint of the firm in terms of the environmental impact of the production processes. Then, in scenario 1 emissions can only be reduced by losing sales.

In general, the results indicate that investments and capacity expansion programs strengthen the economic benefit while reducing the carbon footprint. In fact, investments and capacity expansion enable firms to lessen the number of allowances to purchase and to increase profits. Figure 4.6 illustrates profits for scenarios 1 and 2 under various parameter settings.

As an illustrative example, Figure 4.7 shows the difference per cost when the allowance price and the assistance factor are set at $30/allowance and 100%, respectively. With a fill rate of 99%, the profit is augmented on average by 5.78%, which amounts to $165,000,000 over the whole planning horizon, and $8,700,000 yearly. Production cost, raw material acquisition, and carbon trading account for the greatest difference in costs. It can be seen that when the carbon price reaches a certain value, the profit slope becomes positive. This situation occurs when it becomes more expensive to fill demand than to comply with environmental legislation. In that case, sales are lost, and allowances are auctioned. The latter means that the company is no longer profitable, and survives by selling allowances, which definitely does not make economic sense. Therefore, we did not consider scenarios involving this behavior, and such cases are presented only for illustrative purposes.

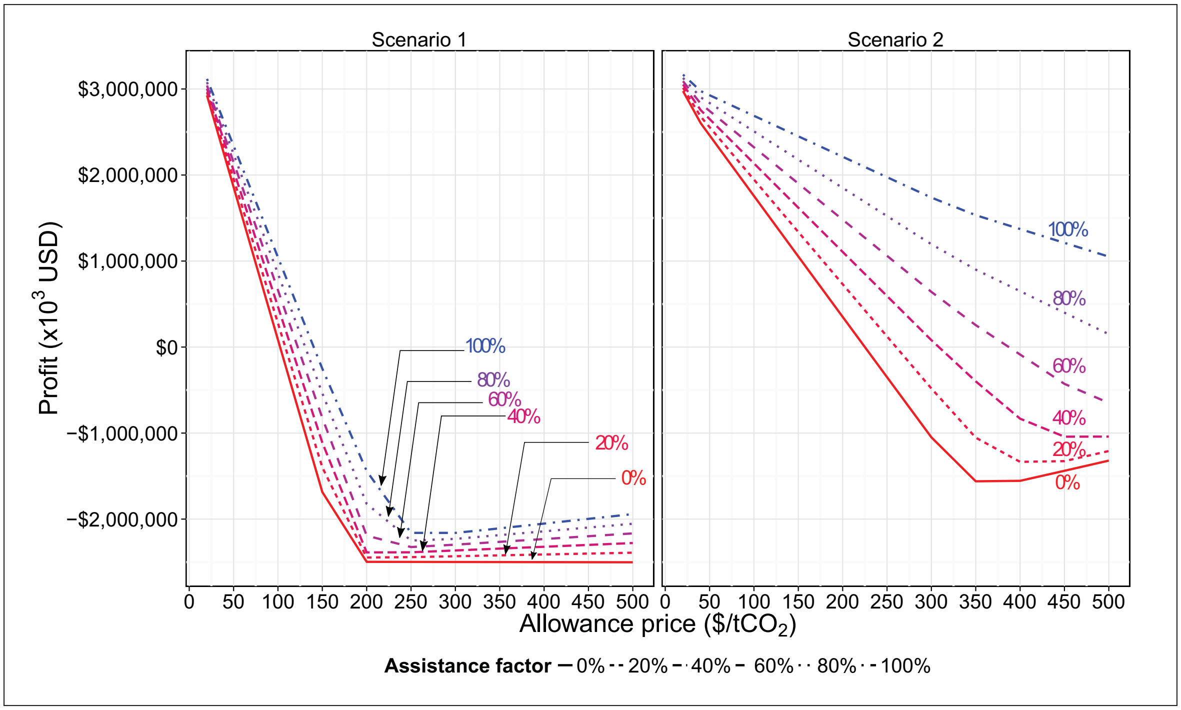


Figure 4.6 Total profit for different allowance price and assistance factor cases

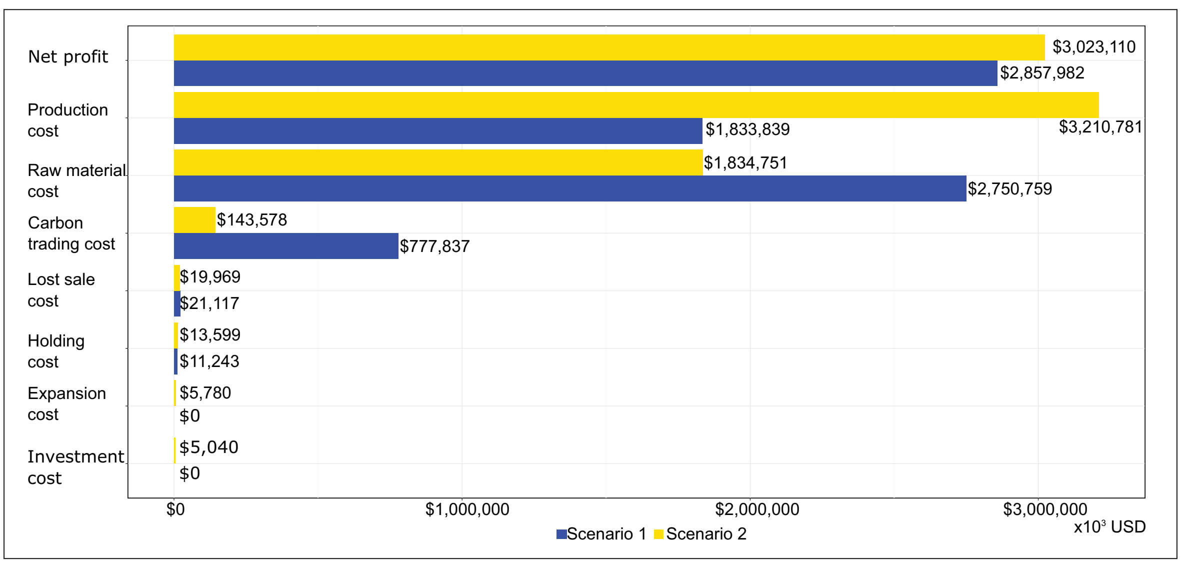


Figure 4.7 Cost comparison, allowance price $30/allowance

Figure 4.8 shows the environmental impact for each scenario. Investment in carbon projects and capacity expansion strategies enable the shrinkage of carbon footprint levels. On average, when the allowance price and the assistance factors are respectively set at $30/allowance and

100% in scenario 2, GHG levels are cut down by 52 % which amount to 23.333 $MtCO_2$ over the whole planning horizon, and to 1.228 $MtCO_2$ annually.

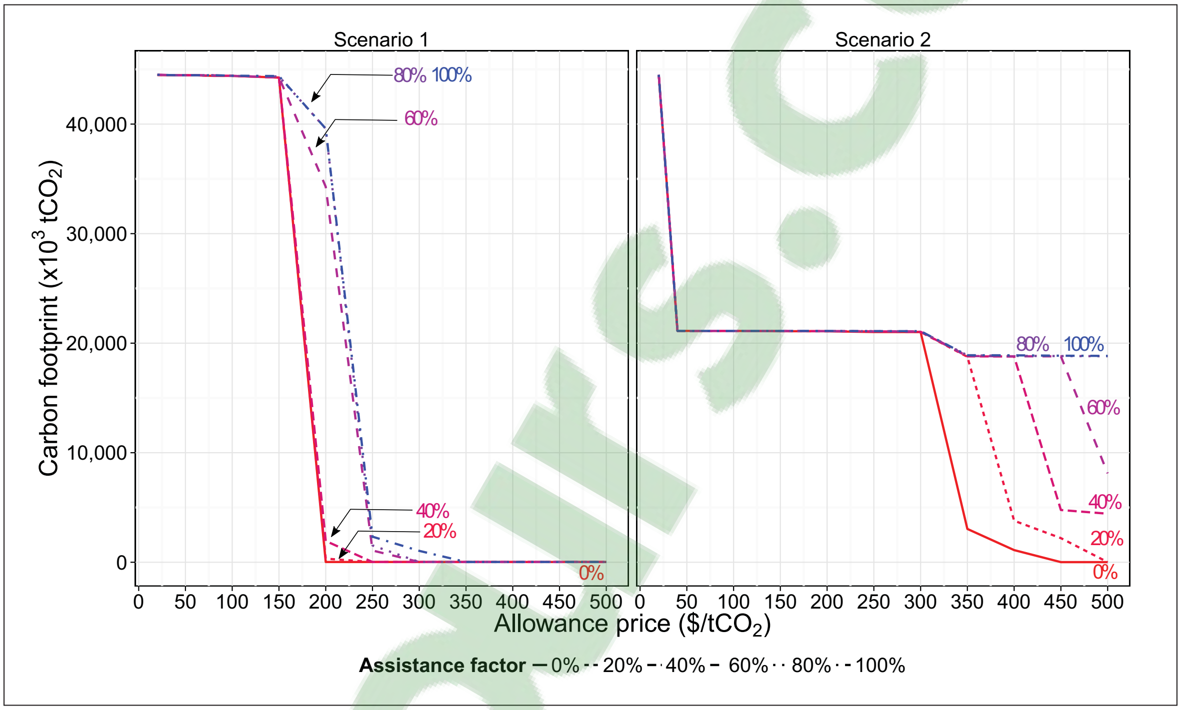


Figure 4.8 Carbon footprint under different allowance price and assistance factor cases

Since in scenario 1, it is only possible to cut emission by losing sales, as allowance prices increase and assistance factors decay, the difference between both scenarios is that much greater. The latter point can be proven by exploring the scenario where the allowance price and the assistance factor are respectively set at $200/allowance and 100%, illustrated by Figure 4.9. In this scenario, the difference in the carbon footprint is similar to the previous one ($30/allowance). The $CO_2$ reduction is 46.6%, which amounts to 18.468 $MtCO_2$ over the whole planning horizon. However, the difference in profit is highly significant in this case, and comes in at 253%. The fill rate is still 99%.

The effect of investments and capacity expansion can be further explored by analyzing the fill rate. Figure 4.10 illustrates the fill rate for the different scenarios and parameter settings. The

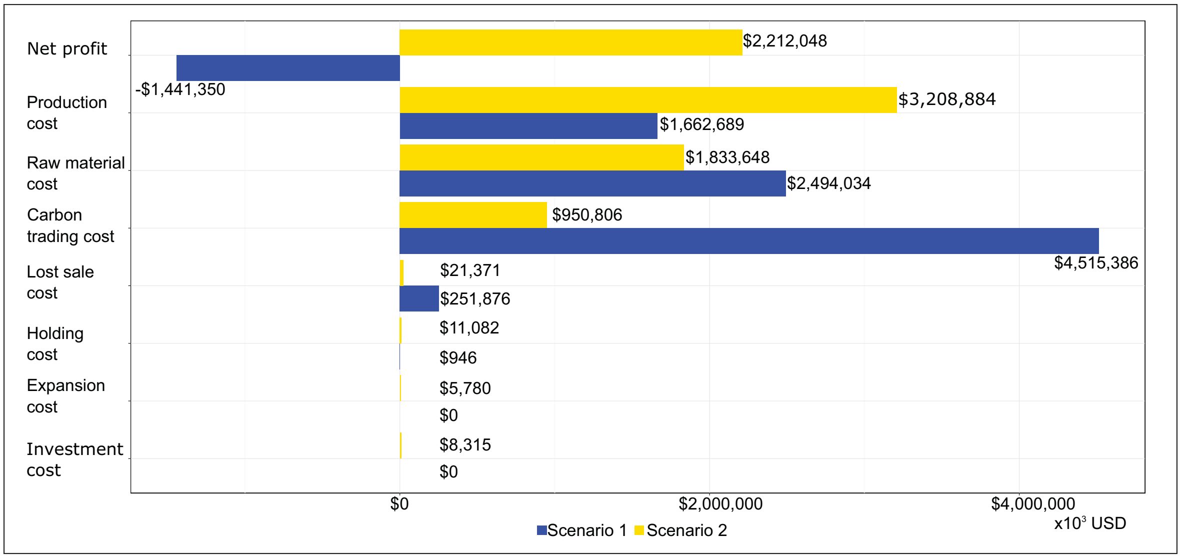


Figure 4.9 Cost comparison, allowance price $200/allowance

allowance price exceeds the marginal profit at prices higher than $150. Then, sales are lost, and the carbon footprint is reduced. In contrast, in scenario 2 lost sales appear for prices higher than $300.

From the analysis of the profit, carbon footprint, and fill rate, our results suggest a positive and a negative correlation between the assistance factor and the allowance price with the total profit, respectively. The higher the allowance price, the lower the profit. In scenario 1, when the allowance price is greater or equal to $150/allowance, it is no longer profitable to satisfy the total demand. The same circumstance arises in scenario 2 for allowance prices higher than $300. Likewise, it is clear the profit is sensitive to the free allowance allocation. Moreover, its effect is accentuated by high allowance prices. In particular, in scenario 1 the correlation of the assistance factor and profit is stronger because it is impossible to cut the carbon footprint. In contrast, in scenario 2, the importance of the assistance factor increases for allowance prices greater than $300.

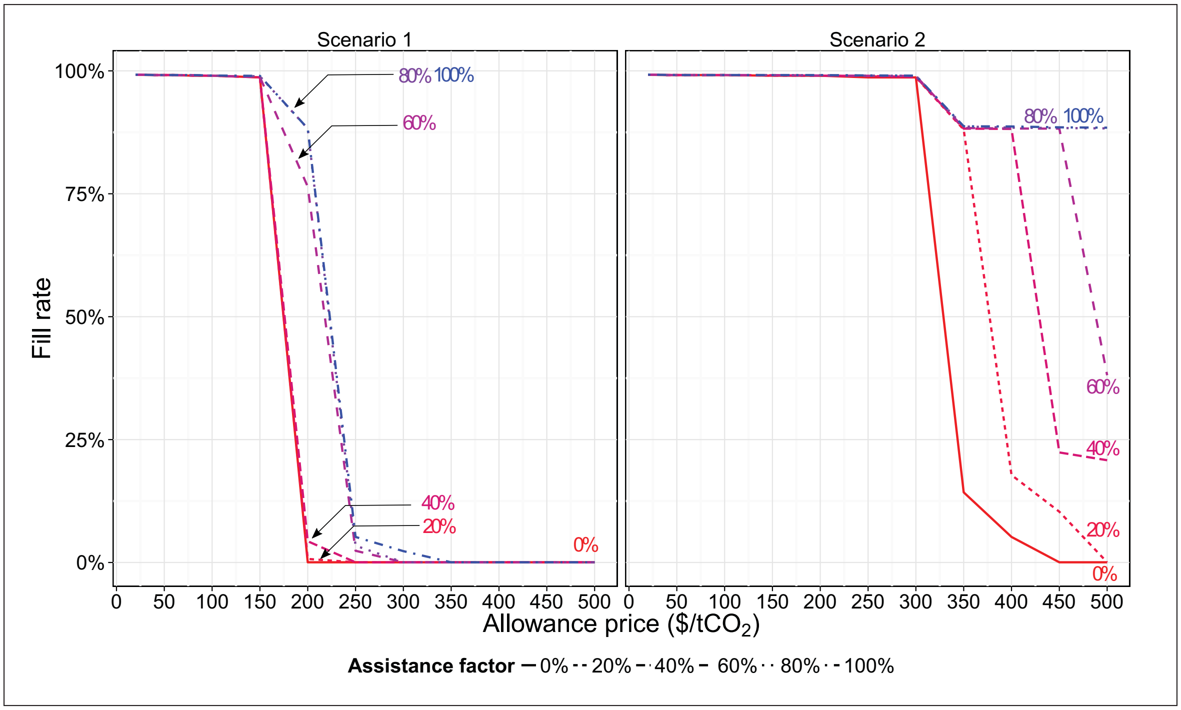


Figure 4.10 Service level under different parameter settings

#### 4.4.4.2 Environmental investments and capacity expansion strategy

Investments and capacity expansion would be triggered by the relation between allowance prices and marginal revenue. Higher allowance prices encourage stronger investments. Environmental investments and capacity expansion are carried out as follow.

In our numerical example, capacity expansion cost is lower than allowance prices for values greater than $20. For this reason, the maximal remanufacturing capacity expansion is carried out with allowance prices higher than $20, regardless of the assistance factor. Similarly, investments are made only when their costs are lower than the allowance price. We can differentiate two zones (investments in net present value): 1) low investment level (average investments of $5,000,000 equivalent to 7,223 $MtCO_2$), and 2) high investments (average investments of $8,900,000 equivalent to 12,000 $MtCO_2$). Low investment levels are observed for allowances prices below $100/$tCO_2$.

In the last section, we showed that there is a price from which allowance prices cause the overall production cost to be higher than revenues, resulting in lost sales. For scenario 1, this arrives for prices higher than \$150, and it is at this value that investments are intensified. Likewise, in scenario 2, we can also distinguish a critical point at \$300. At this point, other cost-effective investments must be made. This is proof that a cap-and-trade scheme encourages constant environmental improvement, in order to avoid reaching the point where the cheapest option to mitigate emissions is to lose sales.

#### 4.4.4.3 Production planning and inventory control strategy

In the scenarios under study, production capacities were set lower than demand. Then, in scenario 1, the manufacturing capacity was used to the maximum, and only decreased when sales were lost. On the other hand, in scenario 2 when remanufacturing is used (allowance prices higher than \$20/allowance), it is used to its maximum capacity and reduced when sales are lost as well.

Regarding inventory control, there is evidence that the serviceable inventory is positively correlated with the fill rate and negatively correlated with allowance prices, as illustrated in Figure 4.11. The system tries to reduce the holding cost in order to absorb the costs resulting from allowance purchasing. We assume that this would also lead to higher production capacities.

#### 4.4.4.4 Carbon management strategy

The impact of investments and the capacity expansion strategy can also be observed in the carbon management strategy.

Figure 4.12 shows the average allowance holding level per period. As can be seen, the allowance holding curve shows troughs and peaks. The allowance holding strategy is negatively correlated with the fill rate. A peak in the allowance holding level denotes a major decrease in the service level. Meanwhile, a slow decrease in the allowance holding level denotes a stable service level, with an increasing carbon price. The curve of scenario 1 appears softer, with

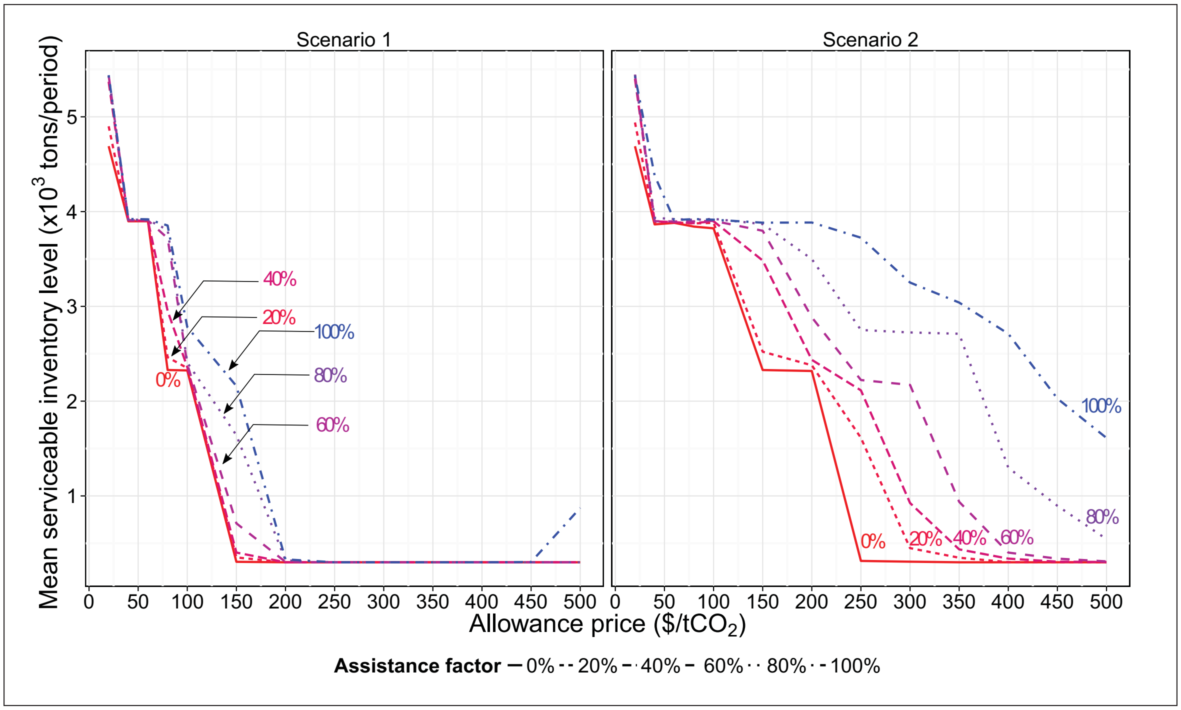


Figure 4.11 Average serviceable inventory level for scenarios 1 and 2 under different parameter settings

smoother troughs and peaks, than that of scenario 2. The fact that capacity and environmental investment bring more allowances to the system makes the curve of scenario 2 less soft.

Carbon sales and purchases support the behavior of the holding account and purchase. Figures 4.13 and 4.14 respectively illustrate the allowance sale and purchase. The sale of allowances is only considered when the fill rate is decreased. On the other hand, carbon purchase is stables and linked to the sections defined above, and decreases when higher investments are made.

Since we assumed an average purchase and selling price throughout the whole planning horizon, allowances are therefore always purchased during the current period, and never in advance.

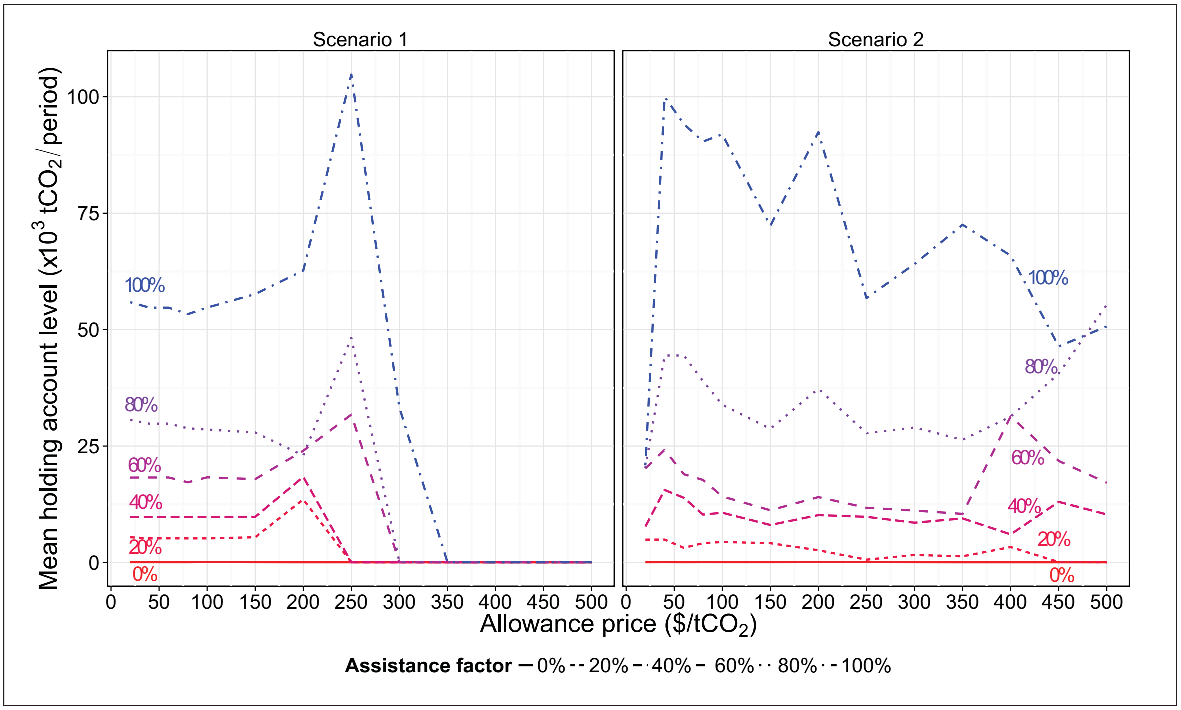


Figure 4.12 Average emission holding level for scenarios 1 and 2 under different parameter settings

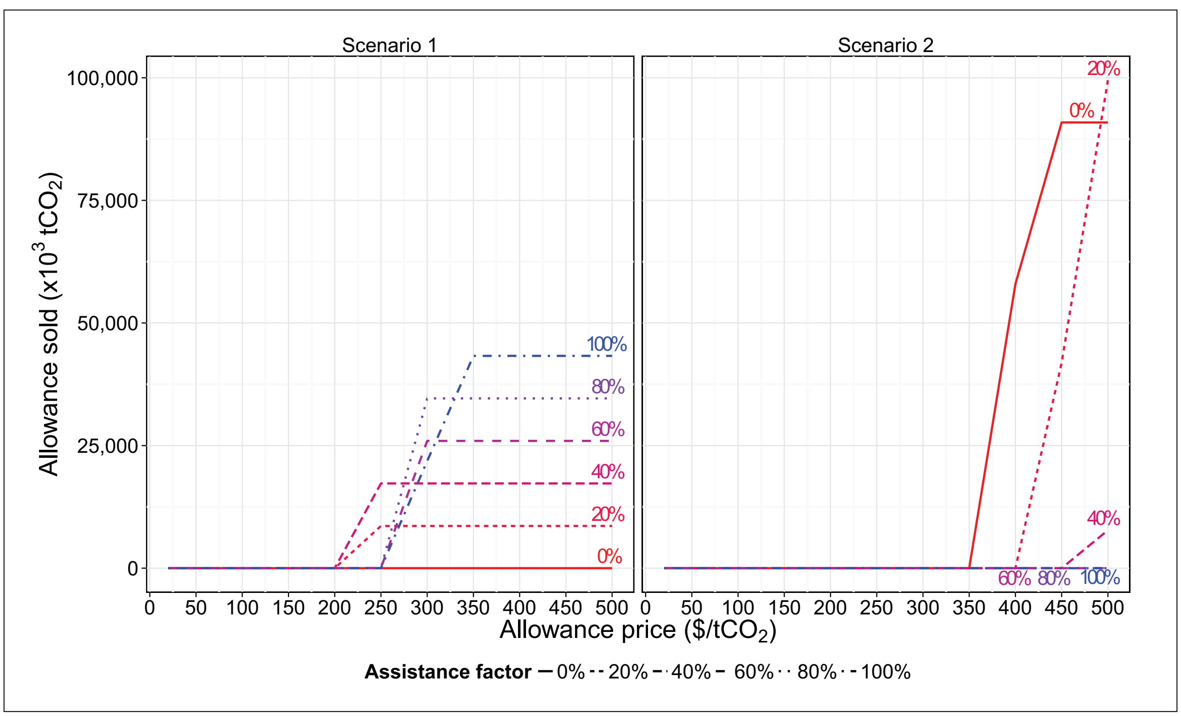


Figure 4.13 Carbon sale strategy for scenarios 1 and 2 under different parameter settings

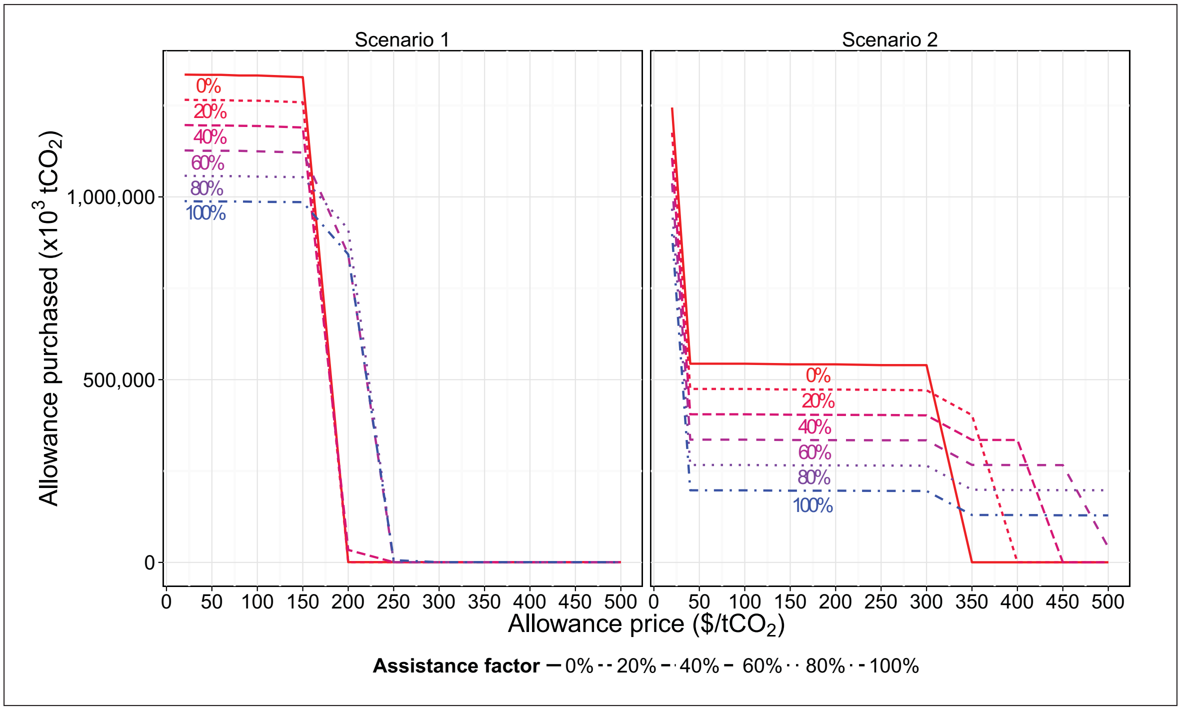


Figure 4.14 Carbon purchase strategy for scenarios 1 and 2 under different parameter settings

### 4.4.5 Sensitivity analysis

In the case study presented above, we stated a positive and negative correlation of the assistance factor and allowance price. To further explore the effect of the assistance factor, we studied four additional scenarios with different environmental impacts by the manufacturing and remanufacturing processes.

Table 4.3 shows the correlation that the allowance price and the assistance factor have on the total profit for the different scenarios. The assistance factor has a stronger correlation when the environmental impact of manufacturing and remanufacturing is closer to the emission benchmark. As the industry carbon footprint gets closer to the emission benchmark, the fewer the allowances purchased.

Table 4.3 Correlation factors

| | Manufacturing ($tCO_2$/ton) | Remanufacturing ($tCO_2$/ton) | Spearman correlation ($\rho$) | |
|---|---|---|---|---|
| | | | Allowance price | Assistance factor |
| Scenario 2 | 4 | 1.9 | -0.90 | 0.37 |
| Scenario 3 | 2.5 | 1.6 | -0.85 | 0.45 |
| Scenario 4 | 5.0 | 1.6 | -0.84 | 0.48 |
| Scenario 5 | 2.5 | 2.4 | -0.92 | 0.28 |
| Scenario 6 | 5 .0 | 2.4 | -0.90 | 0.31 |

### 4.5 Discussion

• Carbon abatement face limits when investments and capacity sizing are impossible. While tactical decisions have already been aligned with environmental strategies, emission reduction cannot be accomplished without compromising the economic performance of the system. Moreover, as a result of allowance price increases, the production cost would match or exceed revenues, and sales would be lost.

Our findings indicate that investments and capacity expansion strategies help counteract the effects of carbon pricing and allowance availability. This yields to an increase in earnings and a reduction in the carbon footprint of the firm.

• The cap-and-trade scheme encourages capacity expansion and investments in carbon reduction strategies. In our system, decisions are made based on a trade-off between the different options to curb emissions: strategic decisions (i.e.: capacity expansion and investments in low-carbon abatement technology) versus tactical decisions (i.e.: purchase of allowances). Our results suggest that investments must be made before or, at least, when the carbon price makes the production cost higher than sale prices.

This indicates that a cap-and-trade scheme immerses companies in an environment where constant green investments are mandatory. Otherwise, the production cost would exceed revenues and sales prices would have to be raised. Since more clients are willing to pay higher prices for greener products, but not the inverse, firms in this situation would face severe risks. This idea goes-in-hand with the latest climate programs supporting zero GHG emission companies.

Cap-and-trade systems present the company with some uncertainty regarding carbon prices and availability. As a result, one would probably think that final inventories would increase. However, to decrease overall expenses and absorb pollution costs, inventories would have to be depleted, and capacities increased. Moreover, to respond to the uncertainty of the carbon market, holding emissions would be crucial. Emission holding provides environmental stability to the system; increased stability enables the firm to make steadier decisions regarding the number of allowances to purchase and the amount of emissions to surrender.

• Decision-making changes when allowance prices, and assistance factors are permuted. It could generally be observed that allowance prices do affect decisions and, therefore, profits: When the allowance price rises, profits decrease. Specifically, if the allowance price exceeds a threshold price, greater environmental investments would be preferred. The size and the decision period at which investments and capacity extensions might be made vary from scenario to scenario.

There is evidence that the assistance factor has a significant impact on profit. Assistance factors foster an environmental stability that may result in lower allowance purchase and additional gains from carbon sales. We assume its influence intensifies along with the allowance price and the availability of allowances on the carbon market. Results of our further analysis of the impact of the environmental impact of manufacturing and remanufacturing support the idea that as the industry's environmental impacts approaches benchmark values, the effect of the assistance factor strengthens.

Finally, as policy-makers seek to strengthen legislation to accelerate the transition, assistance factors represent the solution. Assistance factors must be set such as to bring the companies closer to their threshold price, thereby forcing them to make greener investments.

## 4.6 Conclusion

In this paper, we studied the interaction between strategic and tactical decisions under the cap-and-trade mechanism. We showed how carbon abatement strategies, capacity expansion, and carbon management schemes are essential to curb carbon emissions without jeopardizing economic objectives.

We drew general conclusions concerning how investments and capacity sizing strategies influence profits. We analyze and provide insight on how serviceable and allowance inventory levels react to such strategies and support the objective of profit maximization. Clearly, the potential of investments and capacity expansion depends on several factors. In particular, our results provide evidence that pricey carbon allowances reduce profit while increasing investments. Meanwhile, higher assistance factors contribute to greater environmental stability, which is reflected in lower carbon purchases and greater profits.

Our study can be extended in future works. Allowance availability and its price are uncertain. Therefore, it seems worthy to integrate allowance availability and price uncertainty throughout the planning horizon in decision-making. Furthermore, given the significant environmental repercussions of transport, it also seems worthy to extended our analysis to study the effect of transport environmental impact on decision-making.

**Acknowledgements**

We thank Mr. Ouhimmou for his helpful discussions and comments.

## GENERAL CONCLUSION

The main objective of this research was to enhance the understanding of the role of inventory control to achieve cost-effective and social and environmentally friendly supply chains. We found that there was a knowledge gap in understanding the role of inventory control to enhance the sustainable performance of firms. Moreover, we identified that little was known about how inventory policies have to be re-designed to cope with environmental constraints. Therefore, we studied the potential of inventory control to achieve sustainable development goals.

As previously mentioned, our research objectives can be grouped as:

- Define the scope of current inventory policies to achieve environmental performance.
- Identify critical factors in tactical planning in light of environmental constraints.
- Determine the opportunities of joint strategic and tactical planning for increasing the environmental performance of firms.

Our results suggest that inventory control can help to comply with sustainable objectives. In particular, the redesign of inventory policies: 1) provides the company with the flexibility to react to the additional uncertainties from the carbon market; 2) balances production capacity, demand and carbon credits; and 3) enables firms to take advantage of the carbon market to maximize their long-term wealth while minimizing environmental effects of production. In the sections that follow, we discuss in more detail our findings, implications, and future perspectives.

clicours.com

## Findings

### The scope of current inventory policies to achieve environmental performance

Our first research question sought to determine if present inventory policies can meet environmental constraints. We strove to identify, if existent, the benefits of restructuring inventory management.

Chapter 2 was intended to investigate this question. We addressed an infinite horizon problem with remanufacturing. The proposed Markovain decision process (MDP) model integrates a cap-and-trade scheme into the structure of the problem. We formulated the model as a minimization problem to study the increase in costs. We compared the cost-efficiency and environmental accomplishment of a system without environmental restrictions to a system subject to carbon abatement mechanisms. Furthermore, we provided insight into the structure of inventory and carbon management strategies and performed a numerical analysis on emission-cap and allowance prices.

Our outcomes demonstrate that if current inventory policies are kept, there is a clear increment in total costs. Inventory policies might help enable better environmental performance without a significant rise in cost. These opportunities intensify by increasing allowance prices and tighter emission-cap. Regarding the structure of the new policies; it is not as simple as that of a conventional scenario. Moreover, emission control becomes an additional opportunity to reach sustainability goals.

In summary, inventory policies must be re-designed 1) to cope with environmental legislation without making a major cost increase, and 2) to take advantage of the carbon market. Also, we noted that environmental parameters have a significant effect on decision-making, and it seems worthy of further exploration.

### Critical factors in tactical planning in light of environmental constraints

In our second question, we focused on understanding the impact of environmental parameters and their effect on decision making. More specifically, we investigated the effect of permuting such parameters on inventory control.

Chapter 2 was an initial attempt to understand the impact of environmental parameters in inventory control. We refine our understanding of environmental policies in Chapter 3, and extend the model of Chapter 2 to a finite-horizon approach. We studied a stochastic inventory model for a product recovery system, and proposed a genetic algorithm, extending our results to larger instances. We compared two carbon abatement strategies (i.e. direct-cap and emission trading regulation), and offered insight into the benefits and pitfalls of both environmental policies.

Our results indicate that carbon prices and the emission-cap are key factors affecting inventory control. In particular, there are environmental severity levels that affect the net benefit obtained from the redesign of policies. From the comparison of environmental policies, the financial benefit of coping with environmental constraints depends on the regulation. Cap-and-trade scheme and direct-cap legislation might mitigate carbon emissions, but the cap-and-trade scheme enables the company to get benefits from the sale of allowances while a direct-cap would just fill the minimal emission abatement required.

In Chapter 3, we found that inventory control provides flexibility to the systems to balance production cost, demand, and carbon prices; however, when environmental policies are very restrictive, a parallel strategic decision, such as carbon abatement investments, must be made.

### The role of the integration of hierarchical decision levels on firm's environmental performance

Through Chapters 2 and 3, we provided a clear justification of why inventory control must be restructured to cope with environmental issues. Nevertheless, sustainability calls for a holistic view of supply chains, and so we did not restrict our research to the tactical level. In our last research question, we focus on identifying the potential of inventory control on sustainability performance. To this end, we extend our past results to the strategic level.

In Chapter 4, we extended the results of Chapter 3 to the strategic level. We study a maximization problem where decisions simultaneously consist of carbon abatement investment, capacity sizing, inventory and production planning, and carbon management strategies. Finally, we performed a profit comparison to prove the economic and environmental benefits of integrating strategic and tactical decision levels.

Our results suggest that inventory control plays a key role in increasing the environmental performance of firms by providing a way to balance costs, environmental requirements, and production capabilities, although, there are limits to the scope of tactical planning on carbon mitigation. An integrated approach provides a solution to these treating situations characterized by pricey carbon credits, and/or tight emission-caps. In fact, a cap-and-trade scheme thrives on a situation where constant green investments are essential to survive. Then, joint strategic and tactical planning can lead to economic improvements by providing the system with the stability needed to make steadier decisions regarding the sale and purchase of carbon credits.

**Managerial implications**

In this work, we expanded knowledge regarding the ways that inventory control helps to increase sustainable performance of firms. In particular, we increased the understanding of the effect of environmental policies on decision-making. Several practical implications can be derived from our work, as detailed in the following sections.

**Implications for decision-makers**

Decision-makers need tools for integrating sustainability. This study stresses the benefits of inventory control on the quest of meeting sustainable development goals. Decision-makers can, therefore, use the results provided in this work to establish inventory control as a means for outperforming competitors. Inventory control is an advantageous complementary tool that can help to control cost and mitigate the environmental effects of production. The set of guidelines provided may help businesses to identify the strength and speed necessary for efficiently incorporating environmental policies into their production activities. In addition, we identified crucial parameters that need to be taken into consideration while making decisions.

**Implications for policy-makers**

We offer a set of guidelines that may lead to a more appropriate legislation. From our results, it is clear that environmental policies help to reduce the carbon footprint of a company. In particular, we provide proof that environmental parameters interact. Additionally, parameter value and interaction have a key significance regarding the effect of environmental policies.

In this study, we give insight into carbon prices and emission-cap values that trigger carbon mitigation, while simultaneously not putting companies' survival in peril. Finally, our results help define more appropriate levels of enforcement among and between the different sectors.

**Social implications**

In this work, we do not explore the integration of social aspects such as job stability versus flexible capacity. However, one of the implications of our findings is that we provide a means to manufacture greener products without significantly increasing costs. This might result first, in greener products offered at prices similar to those of conventional products and second in a reduced environmental impact on communities where firms are established.

**Limitations**

The results and conclusions of this work are not without their limitations.

Our use of simplified case studies inspired by covered sectors enabled us to better understand the integration of environmental activities; however, this limits the generalization of our results. Other factors such as quality of returned items must be integrated. In addition, we focused our attention on understanding and characterizing the structure of the inventory policies. Therefore, since the size of safety stocks depends on the type of inventory policy we concentrated on gathering knowledge on the behavior of inventory policies and we did not investigate the impact on safety stock.

Another limitation of our work is that although sustainability calls for a holistic view of the system, knowledge of the impact of inventory control was not clear. We needed to fill those gaps before adding other sources of complexity. Hence, we did not integrate activities with a high carbon footprint such as transport.

Finally, uncertainties such as carbon availability on carbon management strategies are also excluded. The understanding of environmental regulation was still in its infancy, and this prevented us from including more advanced dynamics. Despite this, we believe our findings provide a step forward in knowledge around inventory control subject to environmental constraints.

**Further research**

Limitations and results from Chapters 2, 3 and 4 open the door to further research.

• Models presented in Chapters 2, 3 and 4 can be extended in multiple ways. In Chapters 2 and 3 we focused only on the characterization of inventory policies. Further research must be done to determine proper safety stock levels to mitigate the effect of uncertainty. In Chapters 2 and 3, we consider same quality for manufacturing and remanufacturing items. However, in multiple scenarios the quality of remanufacturing products is inferior to that of manufacturing items. The resulting model can further contribute to capturing the dynamics of other manufacturing environments. In Chapter 4, we assume allowance prices are fixed over all the planning horizon. Note that allowance prices are set by governments, and supply and demand. Uncertainties brought by allowance prices may impact carbon management strategies and in consequence, production planning and inventory strategies. Extending the proposed model to consider uncertainties of the carbon market may further improve the understanding of the impact of environmental laws. Finally, another avenue of research would be to extend the proposed models to consider transport decisions. It is well known that transport is one of the main sources of emission generation. Integration of transport decisions into inventory control seems to be a logical step in the mission to achieve cost-effective and environmentally friendly supply chains.

• Even though environmental achievement makes social improvements, there is a need to understand the benefits of inventory control on other societal aspects, such as employee turnover and working hours. It has been proven that inventory control can help to increase flexibility and reduce uncertainties. Therefore, inventory control might help to balance business, environment and employee needs. For instance, a company can trust to redesign their inventory policies as a means to keep a permanent workforce and prevent stock-outs due to a fluctuating demand or production constraints. There is an ample opportunity for further studying how inventory control supports social goals.

• Legislation trends suggest that environmental policies would enforce stricter requirements regarding carbon prices and availability. Joined to the increasing pressure from clients, the repercussions of no satisfying environmental laws to the environmental reputation and finances of a firm would be too significant to disregard. Consequently, as this tendency continues to grow, other practices such as carbon management would become major players in the attempt to achieve sustainable supply chains. The characteristics of carbon management make it similar to an inventory problem where decisions regarding time and quantity to purchase and sell carbon credits need to be addressed. Because of their similarity to inventory control problems, carbon management strategies eventually might enable 1) the building of more flexible, sustainable supply chains capable of reacting to the uncertainty of supply and the volatility of carbon prices, and 2) the creation of more prosperous supply chains that would take advantages of the carbon market. A deeper understanding of carbon management strategies seems worthwhile.

• Despite our insight into the potential of inventory policies for improving the sustainable performance of a firm, forthcoming research should give more guidance to managers on the ways to integrate the proposed policies. Inventory policies might be translated into enterprise resource planning (ERP) systems. Accordingly, studies on how new policies can be incorporated into such tools must be conducted.

**Conclusion**

Sustainability calls for a holistic view of the supply chain. As there is no thorough understanding of sustainability at all decision levels, i.e. tactical and operational, this task would have several technical drawbacks. Therefore, the aim of this thesis was to increase the understanding of the role of inventory control in achieving sustainable goals. We provided evidence of its influence, benefits, and limitations on this task. It is a milestone in the understanding of how firms can help to ensure the sustainability of their activities.

Our objective was to provide guidance not only for inventory control but also for overall decision-making. We wanted to determine how decision-makers need to adjust their strategies to meet and outperform economic, and environmental targets. To achieve this goal, we used mathematical models. Because the structure of the supply chain and several parameters of environmental laws are particular to each scenario, no single model could capture all necessary aspects and dynamics. That is why through this research, we study different case studies which were focused on analyzing and explaining various synergies. The complete set of our studies provides a big picture of the role of inventory control on coping with environmental constraints. Overall, we can see that environmental constraints and their parameters have an impact of inventory policies. Inventory decision change when among its objectives is to achieve carbon abatement.

Our results also confirm that redesigning decision-making into the environmental path is not an easy task and according to the global trends, it will not become easier. So far, several environmental laws are not mandatory, but there is a strong likelihood that they would become. Thus, companies need to rethink their decisions promptly. Our research presents valuable insights considered along with aspects such as political and societal issues can assist the decision-maker to make the best possible choice.

## BIBLIOGRAPHY


Absi, N., S. Dauzére-Pérès, S. Kedad-Sidhoum, B. Penz, and C. Rapine. 2013. "Lot sizing with carbon emission constraints". *European Journal of Operational Research*, vol. 227, n° 1, p. 55–61.

Agrawal, S., R. K. Singh, and Q. Murtaza. 2015. "A literature review and perspectives in reverse logistics". *Resources, Conservation and Recycling*, vol. 97, p. 76-92.

Ahi, P., C. Searcy, P. Ahi, and C. Searcy. 2013. "A comparative literature analysis of definitions for green and sustainable supply chain management". *Journal of Cleaner Production*, vol. 52, p. 329-341.

Ahiska, S. S. and R. E. King. 2010. "Inventory optimization in a one product recoverable manufacturing system". *International Journal of Production Economics*, vol. 124, n° 1, p. 11 - 19.

Alinovi, A., E. Bottani, and R. Montanari. 2012. "Reverse Logistics: a stochastic EOQ-based inventory control model for mixed manufacturing/remanufacturing systems with return policies". *International Journal of Production Research*, vol. 50, n° 5, p. 1243-1264.

Andersson, K., M. Eide, and U. Lundqvist. 1998. "The feasibility of including sustainability in LCA for product development". *Journal of Cleaner Production*, vol. 6, p. 289-298.

Aronsson, H. and H. M. Brodin. 2006. "The environmental impact of changing logistics structures". *The International Journal of Logistics Management*, vol. 17, n° 3, p. 394-415.

Arslan, M. and M. Turkay. 2013. "EOQ Revisited with Sustainability Considerations". *Foundations of Computing and Decision Sciences*, vol. 38, n° 4, p. 223-249.

Bai, C. and J. Sarkis. 2010. "Integrating sustainability into supplier selection with grey system and rough set methodologies". *International Journal of Production Economics*, vol. 124, n° 1, p. 252-264.

Barari, S., G. Agarwal, W. Zhang, and B. Mahanty. 2012. "A decision framework for the analysis of green supply chain contracts: An evolutionary game approach". *Expert Systems with Applications*, vol. 39, p. 2965-2976.

Battini, D., A. Persona, and F. Sgarbossa. 2014. "A sustainable EOQ model: Theoretical formulation and applications". *International Journal of Production Economics*, vol. 149, p. 145-153.

Bauer, J., T. Bektaş, and T. G. Crainic. 2009. "Minimizing greenhouse gas emissions in intermodal freight transport: an application to rail service design". *Journal of the Operational Research Society*, vol. 61, n° 3, p. 530-542.


clicours.com

Bayındır, Z. P., R. Dekker, and E. Porras. 2006. "Determination of recovery effort for a probabilistic recovery system under various inventory control policies". *Omega*, vol. 34, n° 6, p. 571-584.

Bazan, E., M. Jaber, and A. Saadany. 2015a. "Carbon emissions and energy effects on manufacturing–remanufacturing inventory models". *Computers & Industrial Engineering*, vol. 88, p. 4151-4178.

Bazan, E., M. Jaber, and S. Zanoni. 2015b. "Supply chain models with greenhouse gases emissions, energy usage and different coordination decisions". *Applied Mathematical Modelling*, vol. 39, p. 5131-5151.

Bazan, E., M. Jaber, and S. Zanoni. 2016. "A review of mathematical inventory models for reverse logistics and the future of its modelling: An environmental perspective". *Applied Mathematical Modelling*, vol. 40, p. 4151-4178.

Ben-Salem, A., A. Gharbi, and A. Hajji. 2015. "An Environmental Hedging Point Policy to control production rate and emissions in unreliable manufacturing systems". *International Journal of Production Research*, vol. 53, n° 2, p. 435-450.

Benjaafar, S., Y. Li, and M. Daskin. 2013. "Carbon Footprint and the Management of Supply Chains: Insights From Simple Models". *Automation Science and Engineering, IEEE Transactions on*, vol. 10, n° 1, p. 99-116.

Bing, X., B. J, and A. Chaabane. 2015. "Global reverse supply chain redesign for household plastic waste under the emission trading scheme". *Journal of Cleaner Production*, vol. 103, p. 28-29.

Bonney, M. and M. Y. Jaber. 2011. "Environmentally responsible inventory models: Non-classical models for a non-classical era". *International Journal of Production Economics*, vol. 133, n° 1, p. 43 - 53.

Bouchery, Y., A. Ghaffari, Z. Jemai, and Y. Dallery. 2012. "Including sustainability criteria into inventory models". *European Journal of Operational Research*, vol. 222, n° 2, p. 229 - 240.

Boukherroub, T., A. Ruiz, and A. Guinet. 2015. "An integrated approach for sustainable supply chain planning". *Computers & Operations Research*, vol. 54, p. 180-194.

Bozorgi, A. 2016. "Multi-product inventory model for cold items with cost and emission consideration". *International Journal of Production Economics*, vol. 176, p. 123-142.

Brandenburg, M. and T. Rebs. 2015. "Sustainable supply chain management: a modeling perspective". *Annals of Operations Research*, vol. 229, n° 1.

Brandenburg, M., K. Govindan, J. Sarkis, and S. Seuring. 2014. "Quantitative models for sustainable supply chain management: Developments and directions". *European Journal of Operational Research*, vol. 233, n° 2, p. 299 - 312.

Brundtland, G., M. Khalid, S. Agnelli, S. Al-Athel, B. Chidzero, L. Fadika, V. Hauff, I. Lang, M. Shijun, and M. M. de Botero. 1987. "Our Common Future (Brundtland report)".

Burns, S. November 2015. "Power Costs in the Production of Primary Aluminum". <https: //agmetalminer.com/2015/11/24/power-costs-the-production-primary-aluminum/>.

Caldentey, R. and S. Mondschein. 2003. "Policy model for pollution control in the copper industry, including a model for the sulfuric acid market". *Operations Research*, vol. 51, n° 1, p. 1–16.

California Air Resources Board. August 2014. "Regulation for the California Cap on Greenhouse Gas Emissions and Market-Based Compliance Mechanisms to Allow for the Use of Compliance Instruments Issues by Linked Jurisdictions".

Carter, C. R. and D. S. Rogers. 2008. "A framework of sustainable supply chain management: moving toward new theory". *International journal of physical distribution & logistics management*, vol. 38, n° 5, p. 360–387.

Chaabane, A., A. Ramudhin, and M. Paquet. 2011. "Designing supply chains with sustainability considerations". *Production Planning & Control*, vol. 22, n° 8, p. 727-741.

Chaabane, A., A. Ramudhin, and M. Paquet. 2012. "Design of sustainable supply chains under the emission trading scheme". *International Journal of Production Economics*, vol. 135, n° 1, p. 37 - 49.

Chen, C. and G. E. Monahan. 2010. "Environmental safety stock: The impacts of regulatory and voluntary control policies on production planning, inventory control, and environmental performance". *European Journal of Operational Research*, vol. 207, n° 3, p. 1280-1292.

Chen, X., S. Benjaafar, and A. Elomri. 2013. "The carbon-constrained {EOQ}". *Operations Research Letters*, vol. 41, n° 2, p. 172 - 179.

Chen, X. and X. Wang. 2015. "Effects of carbon emission reduction policies on transportation mode selections with stochastic demand". *Transportation Research Part E: Logistics and Transportation Review*.

Cholette, S. and K. Venkat. 2009. "The energy and carbon intensity of wine distribution: A study of logistical options for delivering wine to consumers". *Journal of Cleaner Production*, vol. 17, n° 16, p. 1401-1413.

Chopra, S. and P. Meindl, 2015. *Supply Chain Management: Strategy, Planning, and Operation*. ed. 6th.

Chouinard, M., D. S, and A. D. 2005. "Integration of reverse logistics activities within a supply chain information system". *Computers in Industry*, vol. 56, p. 105-124.

Corsano, G., A. Vecchietti, and J. Montagna. 2011. "Optimal design for sustainable bioethanol supply chain considering detailed plant performance model". *Computers & Chemical Engineering*, vol. 35, p. 1384-1398.

Crum, M., R. Poist, C. R. Carter, and P. Liane Easton. 2011. "Sustainable supply chain management: evolution and future directions". *International Journal of Physical Distribution & Logistics Management*, vol. 41, n° 1, p. 46–62.

Curran, M. A. and A. C. Brent. 2005. "Integrating LCIA and LCM". *Management of Environmental Quality: An International Journal*, vol. 16, n° 2, p. 130-142.

Dekker, R., J. Bloemhof, and I. Mallidis. 2012. "Operations Research for green logistics– An overview of aspects, issues, contributions and challenges". *European Journal of Operational Research*, vol. 219, p. 671-679.

Devika, K., A. Jafarian, and V. Nourbakhsh. 2014. "Designing a sustainable closed-loop supply chain network based on triple bottom line approach: A comparison of metaheuristics hybridization techniques". *European Journal of Operational Research*, vol. 235, n° 3, p. 594 - 615.

Dobos, I. 1999. "Production strategies under environmental constraints in an Arrow-Karlin model". *International Journal of Production Economics*, vol. 59, n° 1, p. 337-340.

Dobos, I. 2005. "The effects of emission trading on production and inventories in the Arrow-Karlin model". *International Journal of Production Economics*, vol. 93-94, n° 0, p. 301 - 308.

Dobos, I. 2007. "Tradable permits and production-inventory strategies of the firm". *International Journal of Production Economics*, vol. 108, n° 1-2, p. 329 - 333.

Dong, C., B. Shen, P.-S. Chow, L. Yang, and C. Ng. 2014. "Sustainability investment under cap-and-trade regulation". *Annals of Operations Research*, p. 1-23.

Drake, D., P. R. Kleindorfer, and L. N. V. Wassenhove. 2015. Technology choice and capacity portfolios under emissions regulation. Working Paper.

Elhedhli, S. and R. Merrick. 2012. "Green supply chain network design to reduce carbon emissions". *Transportation Research Part D: Transport and Environment*, vol. 7, n° 5, p. 370-379.

Elkington, J., 1998. *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Conscientious commerce.

Fahimnia, B., J. Sarkis, and F. Dehghanian. 2013. "The impact of carbon pricing on a closed-loop supply chain: an Australian case study". *Journal of Cleaner Production*, vol. 59, p. 210-225.

Fahimnia, B., J. Sarkis, J. Boland, M. Reisi, and M. Goh. 2015a. "Policy insights from a green supply chain optimisation model". *International Journal of Production Research*, vol. 53, n° 21, p. 6522-6533.

Fahimnia, B., J. Sarkis, A. Choudhary, and A. Eshragh. 2015b. "Tactical supply chain planning under a carbon tax policy scheme: A case study". *International Journal of Production Economics*, vol. 164, p. 206–215.

Fahimnia, B., J. Sarkis, and A. Eshragh. 2015c. "A tradeoff model for green supply chain planning:A leanness-versus-greenness analysis". *Omega*, vol. 54, p. 173-190.

Feng, L., J. Zhang, and W. Tang. 2013. "Optimal control of production and remanufacturing for a recovery system with perishable items". *International Journal of Production Research*, vol. 51, n° 13, p. 3977-3994.

Fiksel, J. 2010. "Evaluating supply chain sustainability". *Chemical Engineering Progress*, vol. 106, p. 28-36.

Fleischmann, M. and J. Bloemhof-Ruwaard. 1997. "Quantitative models for reverse logistics: A review". *European Journal of Operational Research*, vol. 103, n° 1, p. 1-7.

García-Alvarado, M. S., M. Paquet, and A. Chaabane. a. "Environmental sustainability for long-term supply chain decisions under cap-and-trade regulation". *Submitted to International Journal of Production Economics*.

García-Alvarado, M. S., M. Paquet, and A. Chaabane. b. "Inventory management under joint product recovery and cap-and- trade constraints". *Submitted to Journal of Cleaner Production*.

García-Alvarado, M. S., M. Paquet, and A. Chaabane. 2014. *An inventory model with recovery and environment considerations*. Technical Report CIRRELT-2014-03.

García-Alvarado, M., M. Paquet, and A. Chaabane. 2012. "Stochastic Inventory Control with Remanufacturing Under the Current Carbon Trading Schemes and Environmental Policies". In *4th International Conference on Information Systems, Logistics and Supply Chain*. (Quebec (Canada), August 26-29 2012).

García-Alvarado, M., M. Paquet, and A. Chaabane. 2013. "Mèthodes de gestion des stocks sous les considérations des législations environnementales". In *10e Congrés International de Génie Industriel*. (La Rochelle (France), June 12-14 2013).

García-Alvarado, M., M. Paquet, and A. Chaabane. 2014a. "Impact of Carbon Emission Regulations on Inventory Management". In *Proceedings of the 2014 Industrial and Systems Engineering Research Conference*. (Montreal (Canada), May 31- June 3 2014).

García-Alvarado, M., M. Paquet, and A. Chaabane. 2014b. "Inventory Control and Environmental Policies". In *5th International Conference on Information Systems, Logistics and Supply Chain*. (Breda (The Netherlands), August 24-27 2014).

García-Alvarado, M., M. Paquet, and A. Chaabane. 2015. "On inventory control of product recovery systems subject to environmental mechanisms". *International Journal of Production Economics*, vol. 165, p. 132–144.

García-Alvarado, M., M. Paquet, and A. Chaabane. 2016. "Integrated strategic and tactical planning under the cap-and-trade scheme". In *8th IFAC Conference on Manufacturing Modelling, Management and Control*. (Troyes (France), June 28-30 2016).

Giarola, S., N. Shah, and F. Bezzo. 2012a. "A comprehensive approach to the design of ethanol supply chains including carbon trading effects". *Bioresource Technology*, vol. 107, p. 175-185.

Giarola, S., A. Zamboni, and F. Bezzo. 2012b. "Environmentally conscious capacity planning and technology selection for bioethanol supply chains". *Renewable Energy*, vol. 43, n° 0, p. 61 - 72.

Gong, X. and S. X. Zhou. 2013. "Optimal Production Planning with Emissions Trading". *Operations Research*, vol. 61, n° 4, p. 908-924.

González-Benito, J. and O. González-Benito. 2006. "The role of stakeholder pressure and managerial values in the implementation of environmental logistics practices". *International Journal of Production Research*, vol. 44, n° 7, p. 1353-1373.

Govindan, K., H. Soleimani, and D. Kannan. 2015. "Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future". *European Journal of Operational Research*, vol. 240, p. 603-626.

Guide, D. V., T. P. Harrison, and L. N. Wassenhove. 2003. "The challenge of closed-loop supply chains". *Interfaces*, vol. 33, n° 6, p. 3-6.

Gurtu, A., M. Jaber, and C. Searcy. 2015. "Impact of fuel price and emissions on inventory policies". *Applied Mathematical Modelling*, vol. 39, p. 1202-1216.

Harris, I., C. Mumford, and M. Naim. 2014. "A hybrid multi-objective approach to capacitated facility location with flexible store allocation for green logistics modeling". *Transportation Research Part E: Logistics and Transportation Review*, vol. 66, p. 1-22.

Hassini, E., C. Surti, and C. Searcy. 2012. "A literature review and a case study of sustainable supply chains with a focus on metrics". *International Journal of Production Economics*, vol. 140, n° 1, p. 69-82.

He, P., W. Zhang, X. Xu, and Y. Bian. 2014. "Production lot-sizing and carbon emissions under cap-and-trade and carbon tax regulations". *Journal of Cleaner Production*, vol. 103, p. 241-248.

Helmrich, M., R. Jans, and W. van den Heuvel. 2015. "The economic lot-sizing problem with an emission capacity constraint". *European Journal of Operational Research*, vol. 241, p. 50-62.

Hervani, A., M. Helms, and J. Sarkis. 2005. "Performance measurement for green supply chain management". *Benchmarking: An International Journal*, vol. 12, n° 4, p. 330-353.

Hoen, K., T. Tan, J. Fransoo, and G. Houtum. 2012. "Effect of carbon emission regulations on transport mode selection under stochastic demand". *Flexible Services and Manufacturing Journal*, p. 1-26.

Hoen, K. M. R., T. Tan, J. C. Fransoo, and G.-J. van Houtum. 2014. "Switching Transport Modes to Meet Voluntary Carbon Emission Targets". *Transportation Science*, vol. 48, n° 4, p. 592-608.

Hollos, D., C. Blome, and K. Foerstl. 2012. "Does sustainable supplier co-operation affect performance? Examining implications for the triple bottom line". *International Journal of Production Research*, vol. 50, n° 11, p. 2968-2986.

Hong, J., J. Zhou, J. Hong, and X. Xu. 2012. "Environmental and economic life cycle assessment of aluminum-silicon alloys production: a case study in China". *Journal of Cleaner Production*, vol. 24, p. 11-19.

Hua, G., T. C. E. Cheng, and S. Wang. 2011. "Managing carbon footprints in inventory management". *International Journal of Production Economics*, vol. 132, n° 2, p. 178-185.

Hugo, A. and E. N. Pistikopoulos. 2005. "Environmentally conscious long-range planning and design of supply chain networks". *Journal of Cleaner Production*, vol. 13, n° 15, p. 1471-1491.

Hugos, M., 2012. *Essentials of Supply Chain Management*. ed. 3rd.

Hutchins, M. and J. Sutherland. 2008. "An exploration of measures of social sustainability and their application to supply chain decisions". *Journal of Cleaner Production*, vol. 16, n° 15, p. 1688-1698.

Inderfurth, K. 1997. "Simple optimal replenishment and disposal policies for a product recovery system with leadtimes". *OR Spectrum*, vol. 19, n° 2, p. 111-122.

Jiang, Y. and D. Klabjan. 2012. *Optimal emissions reduction investment under green house gas emissions regulations*. Technical report.

Jin, M., G. NA, and I. Down. 2014. "The impact of carbon policies on supply chain design and logistics of a major retailer". *Journal of Cleaner Production*, vol. 85, p. 453-461.

Kassinis, G. and A. Soteriou. 2003. "Greening the service profit chain: The impact of environmental management practices". *Production and Operations Management*, vol. 12, n° 3, p. 386-403.

Keating, B., A. Quazi, and A. Kriz. 2008. "In pursuit of a sustainable supply chain: insights from Westpac Banking Corporation". *Supply Chain Management: An International Journal*, vol. 3, n° 3, p. 175-179.

Kim, K., B. Jeong, and H. Jung. 2014. "Supply chain surplus: comparing conventional and sustainable supply chains". *Flexible Services and Manufacturing Journal*, vol. 26, n° 1, p. 5-23.

Kim, N., M. Janic, and V. B. Wee. January 2009. "Trade-off between carbon dioxide emissions and logistics costs based on multiobjective optimization". In *88th Annual Meeting of the Transportation Research Board*. (Washington, D.C. 2009).

Krass, D., T. Nedorezov, and A. Ovchinnikov. 2013. "Environmental Taxes and the Choice of Green Technology". *Production and Operations Management*, vol. 22, n° 5, p. 1035–1055.

Kumar, A., V. Jain, and S. Kumar. 2014. "A comprehensive environment friendly approach for supplier selection". *Omega*, vol. 42, p. 109-123.

Letmathe, P. and N. Balakrishnan. 2005. "Environmental considerations on the optimal product mix". *European Journal of Operational Research*, vol. 167, n° 2, p. 398 - 412.

Li, S. and M. Gu. 2012. "The effect of emission permit trading with banking on firm's production and inventory strategies". *International Journal of Production Economics*, vol. 137, n° 2, p. 304 - 308.

Liu, W., W. Xie, and G. Hua. 2013. Order decision with random demand: A research from the perspective of carbon emission cap and carbon trade mechanism. Chen, F., Yisheng Liu, and Guowei Hua, editors, *LTLGB 2012*, p. 585-593. Springer Berlin Heidelberg.

Manikas, A. and M. Godfrey. 2010. "Inducing green behavior in a manufacturer". *Global journal of business research*, vol. 4, n° 2.

Martel, A., W. M'Barek, and S. D'Amours. 2005. "International factors in the design of multinational supply chains: the case of Canadian pulp and paper companies". *Document de travail DT-2005-AM-3, Centor, Université Laval*, vol. 10.

Mondschein, S. V. and A. Schilkrut. 1997. "Optimal investment policies for pollution control in the copper industry". *Interfaces*, vol. 27, n° 6, p. 69-87.

Mueller, M., D. V. Santos, and S. Seuring. 2009. "The contribution of environmental and social standards towards ensuring legitimacy in supply chain governance". *Journal of Business Ethics*, vol. 89, n° 4, p. 509-523.

Naeem, M., D. J. Dias, R. Tibrewal, P. Chang, and M. Tiwari. 2013. "Production planning optimization for manufacturing and remanufacturing system in stochastic environment". *Journal of Intelligent Manufacturing*, vol. 24, n° 4, p. 717-728.

Pagell, M., A. Shevchenko, M. Pagell, and A. Shevchenko. 2014. "Why Research in Sustainable Supply Chain Management Should Have no Future". *Journal of Supply Chain Management*, vol. 50, n° 1.

Palak, G., S. D. Ekşioğlu, and J. Geunes. 2014. "Analyzing the impacts of carbon regulatory mechanisms on supplier and mode selection decisions: An application to a biofuel supply chain". *International Journal of Production Economics*, vol. 154, n° 0, p. 198 - 216.

Pan, X. and S. Li. 2015. "Optimal control of a stochastic production–inventory system under deteriorating items and environmental constraints". *International Journal of Production Research*, vol. 53, n° 2, p. 607-628.

Purohit, A., R. Shankar, P. Dey, and A. Choudhary. 2015. "Non-Stationary Stochastic Inventory Lot-Sizing with Emission and Service Level Constraints in a Carbon Cap-and-Trade System". *Journal of Cleaner Production*.

Ramudhin, A., A. Chaabane, and M. Paquet. 2010. "Carbon Market Sensitive Sustainable Supply Chain Network Design". *International Journal of Management Science and Engineering Management*, vol. 5, n° 1, p. 29-37.

Rezaee, A., F. Dehghanian, and B. Fahimnia. 2015. "Green supply chain network design with stochastic demand and carbon price". *Annals of Operations Research*, p. 1-23.

Ripley, B. 2016. *tree: Classification and Regression Trees. R package version 1.0-35*. <http://CRAN.R-project.org/package=tree>.

Rosič, H. and W. Jammernegg. 2013. "The economic and environmental performance of dual sourcing: A newsvendor approach". *International Journal of Production Economics*, vol. 143, p. 109-119.

Sánchez, D., L. Amodeo, and C. Prins. 2010. Meta-heuristic approaches for multi-objective simulation-based optimization in supply chain inventory management. Benyoucef, L. and Bernard Grabot, editors, *Artificial Intelligence Techniques for Networked Manufacturing Enterprises Management*, Springer Series in Advanced Manufacturing, p. 249-269. Springer London. ISBN 978-1-84996-119-6.

Sarkis, J. 2003. "A strategic decision framework for green supply chain management". *Journal of Cleaner Production*, vol. 11, p. 397-409.

Schaltegger, S. and M. Csutora. 2012. "Carbon accounting for sustainability and management. Status quo and challenges". *Journal of Cleaner Production*, vol. 36, p. 1-16.

Schaltegger, S. D. and P. Burritt. 2014. "Framing sustainability performance of supply chains with multidimensional indicators". *Supply Chain Management: An International Journal*, vol. 19, n° 3, p. 242-257.

Seuring, S. 2004. "Integrated chain management and supply chain management comparative analysis and illustrative cases". *Journal of Cleaner Production*, vol. 12, p. 1059-1071.

Seuring, S. and M. Müller. 2008. "From a literature review to a conceptual framework for sustainable supply chain management". *Journal of Cleaner Production*, vol. 16, n° 15, p. 1699 - 1710.

Simpson, V. P. 1978. "Optimum Solution Structure for a Repairable Inventory Problem". *Operations Research*, vol. 26, p. 270-281.

Song, J. and M. Leng. 2012. Analysis of the single-period problem under carbon emissions policies. Choi, T.-M., editor, *Handbook of Newsvendor Problems*, volume 176 of *International Series in Operations Research & Management Science*, p. 297-313. Springer New York.

Srivastava, S. K. 2007. "Green supply-chain management: A state-of-the-art literature review". *International Journal of Management Reviews*, vol. 9, n° 1, p. 53–80.

Subramanian, R., S. Gupta, and B. Talbot. 2007. "Compliance Strategies under Permits for Emissions". *Production and Operations Management*, vol. 16, n° 6, p. 763–779.

Testa, F. and F. Iraldo. 2010. "Shadows and lights of GSCM (Green Supply Chain Management): determinants and effects of these practices based on a multi-national study". *Journal of Cleaner Production*, vol. 18, p. 953-962.

Teunter, R. H. and D. Vlachos. 2002. "On the necessity of a disposal option for returned items that can be remanufactured". *International Journal of Production Economics*, vol. 75, n° 3, p. 257-266.

Toptal, A., H. Özlü, and D. Konur. 2014. "Joint decisions on inventory replenishment and emission reduction investment under different emission regulations". *International Journal of Production Research*, vol. 52, n° 1, p. 243-269.

Toptal, A. and B. Çetinkaya. 2015. "How supply chain coordination affects the environment: a carbon footprint perspective". *Annals of Operations Research*, .

Tsai, W. and S. Hung. 2009. "A fuzzy goal programming approach for green supply chain optimisation under activity-based costing and performance evaluation with a value-chain structure". *International Journal of Production Research*, vol. 47, n° 18, p. 4991-5017.

U.S. Environmental Protection Agency. 2001. *The united states experience with economic incentives for protecting the environment*. Report EPA-240-R-01-001.

Validi, S., A. Bhattacharya, and P. Byrne. 2014. "A case analysis of a sustainable food supply chain distribution system—A multi-objective approach". *International Journal of Production Economics*, vol. 152, p. 71-87.

Validi, S., A. Bhattacharya, and P. Byrne. 2013. "Integrated low-carbon distribution system for the demand side of a product distribution supply chain: a DoE-guided MOPSO optimiser-based solution approach". *International Journal of Production Research*, vol. 52, n° 10, p. 3074-3096.

van der Laan, E., G. Kiesmüller, R. Kuik, V. Dimitrios, and R. Dekker. 2004. Stochastic inventory control for product recovery management. R Dekker, e. a., editor, *Reverse logistics: Quantitative models for closed-loop supply chains.*, p. 181-220. Springer, New York.

Veen, J. A. and V. Venugopal, 2014. *Economic and Environmental Performance of the Firm: Synergy or Trade-Off? Insights from the EOQ Model*, volume 197 of *International Series in Operations Research & Management Science*, p. 121-137. Springer US.

von Blottnitz, H. and M. A. Curran. 2007. "A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective". *Journal of Cleaner Production*, vol. 15, n° 7, p. 607-619.

Wahab, M., S. Mamun, and P. Ongkunaruk. 2011. "EOQ models for a coordinated two-level international supply chain considering imperfect items and environmental impact". *International Journal of Production Economics*, vol. 134, n° 1, p. 151-158.

Walker, H., D. L. Sisto, and M. D. 2008. "Drivers and barriers to environmental supply chain management practices: Lessons from the public and private sectors". *Journal of Purchasing & Supply Management*, vol. 14, n° 1, p. 69-85.

Wang, F., X. Lai, and N. Shi. 2011. "A multi-objective optimization for green supply chain network design". *Decision Support Systems*, vol. 51, n° 2, p. 262 - 269.

Wang, W., M. E. Ferguson, S. Hu, and G. C. Souza. 2013. "Dynamic Capacity Investment with Two Competing Technologies". *Manufacturing & Service Operations Management*, vol. 15, n° 4, p. 616-629.

Wirl, F. 1991. "Evaluation of management strategies under environmental constraints". *European Journal of Operational Research*, vol. 55, n° 2, p. 191-200.

Wong, C. 2010. *A study of plastic recycling supply chain.* Technical report.

Xepapadeas, A. 1992. "Environmental policy, adjustment costs, and behavior of the firm". *Journal of Environmental Economics and Management*, vol. 23, n° 3, p. 258-275.

Xu, X., X. Xu, and P. He. 2015. "Joint production and pricing decisions for multiple products with cap-and-trade and carbon tax regulations". *Journal of Cleaner Production*, vol. 112, p. 4093-4106.

Zakeri, A., F. Dehghanian, B. Fahimnia, and J. Sarkis. 2015. "Carbon pricing versus emissions trading: A supply chain planning perspective". *International Journal of Production Economics*, vol. 164, p. 197-205.

clicours.com

Zanoni, S., L. Mazzoldi, and M. Jaber. 2014. "Vendor-managed inventory with consignment stock agreement for single vendor–single buyer under the emission-trading scheme". *International Journal of Production Research*, vol. 52, n° 1, p. 20-31.

Zhang, B. and L. Xu. 2013. "Multi-item production planning with carbon cap and trade mechanism". *International Journal of Production Economics*, vol. 144, n° 1, p. 118 - 127.

Zhao, H., Q. Gao, Y. Wu, Y. Wang, and X. Zhu. 2014. "What affects green consumer behavior in China? A case study from Qingdao". *Journal of Cleaner Production*, vol. 63, p. 143-151.