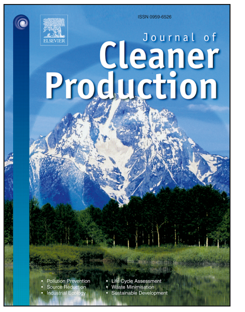

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Abstract

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 Markov 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 such 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

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. (2014a), Fahimnia et al. (2014b), 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 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, we present a literature review on product/material recovery and environmental inventory models. The mathematical formulation of the problem is presented in section 3. Using a numerical example, we illustrate the details of the proposed inventory model and the effect of varying the parameter values in Section 5. We discuss the results of the numerical analysis in Section 6. Our conclusion and proposals for further work are presented in Section 7.

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 Markov 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 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.

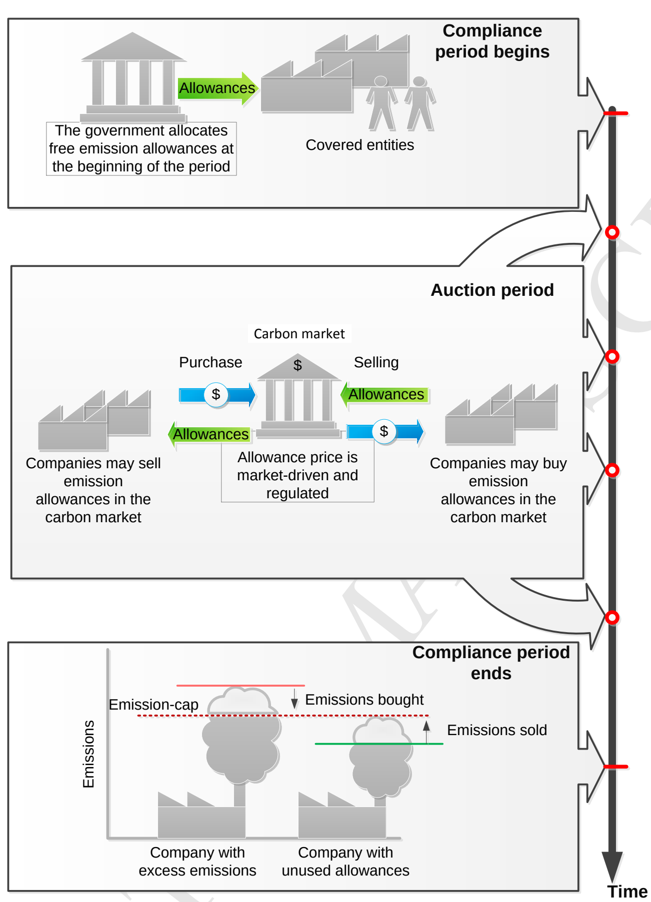

Figure 1: A cap-and-trade scheme

Among published studies with a tactical orientation, Bonney and Jaber (2011) propose an extension of the 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. (2014a) 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. (2014b) 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 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.

3. Problem Definition

In the scenarios that follow, we shall study an 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

Table 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		X		
(Devika et al., 2014)			X	X		
(Fahimnia et al., 2014a)	X	X		X		
(Fahimnia et al., 2014b)	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

cap, and to sell up to a maximum of allowances. In particular, a loose emission cap or a firm stopping its production to trade its carbon credits would result in a company with enough carbon credits to still get a benefit from carbon trading without making any carbon footprint reduction. To prevent those scenarios, we considered the sale of carbon credits is only possible if a β-emission reduction from the previous period has been achieved. In addition, we also considered a minimal recovery constraint at each period, where remanufactured returns must reach a minimal level (α). 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 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 inven-

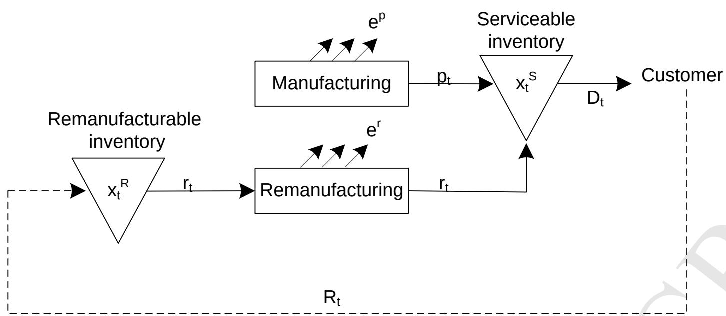

Figure 2: Remanufacturing System

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

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 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 κ^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.

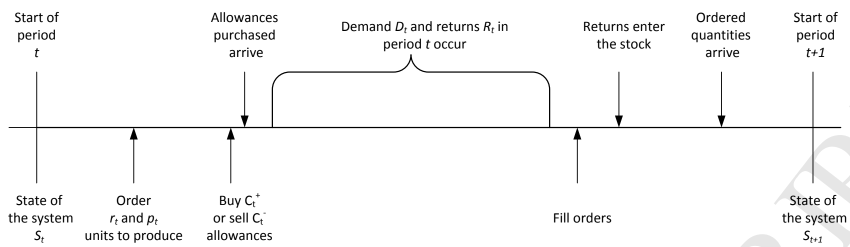

Figure 3: Timing of events

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

Parameters:

κ^r	Remanufacturing capacity
κ^p	Manufacturing capacity
κ^S	Serviceable inventory capacity
κ^{aR}	Recoverable inventory capacity
κ^v	Maximum amount of backlog allowed
κ^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
α	Minimal recovery factor
β	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$t$
ϖ_t	Emissions generated at period *t-1*

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 ϖ_t. The state space $\mathcal{S}$ 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 $\mathcal{A}(s_t)$ 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 $s_t \in \mathcal{S}$ according to a policy π. For a given problem, there might be several possible policies denoted by the set Π. We consider a stationary policy only. Decisions are thus determined by the current state of the system, regardless of time.

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 π, 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 (1) to (5).

Expression (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.

$$x_{t+1}^R = x_t^R + j - r_t \tag{1}$$

The serviceable inventory level at the beginning of period $t+1$ is given by expression (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 κ^v.

$$x_{t+1}^S = \max\{x_t^S - i, -\kappa^v\} + p_t + r_t \tag{2}$$

(3)

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^-).

$$e_{t+1} = e_t - \eta_t(p_t, r_t) - C_t^- + C_t^+ \tag{4}$$

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

$$\varpi_{t+1} = \eta_t(p_t, r_t) \tag{5}$$

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 (6). This is defined in terms of 1) production costs; 2) holding costs and penalties; and 3) allowance trading.

$$f_\pi(x_t^S, x_t^R, e_t, \varpi_t) = \underbrace{\delta(p_t) + \gamma(r_t)}_{\text{production costs}} + \underbrace{H(x_t^R, r_t) + L(x_t^S, r_t, p_t)}_{\text{holding costs and penalties}} + \underbrace{\varrho(p_t, r_t, C_t^+, C_t^-)}_{\text{allowance trading}} \tag{6}$$

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

$$\delta_t(p_t) = C_p p_t$$
$$\gamma_t(r_t) = C_r r_t$$

2. 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 κ^{aR}, surplus products are disposed of at a cost C_d per unit.

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

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 backorder; and 3) the expected cost of lost sales given by a lost sale penalty C_{ls} associated with the unfilled demand going above κ^v.

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

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

3. Environmental cost. Let $\varrho(p_t, r_t, C_t^+, C_t^-)$ 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.

$$\varrho(p_t, r_t, C_t^+, C_t^-) = C_c^+ C_t^+ - C_c^- C_t^-$$

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,

$$\eta_t(p_t, r_t) = e^p p_t + e^r r_t$$

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 π, given the state $(x_t^S, x_t^R, e_t, \varpi_t)$.

$$E_\pi(x_t^S, x_t^R, e_t, \varpi_t) = \eta_t(p_t, r_t) + C_t^- \tag{7}$$

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

$$r_t \leq \min\{x_t^R, \kappa^r\} \tag{8}$$

$$p_t \leq \kappa^p \tag{9}$$

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

$$p_t \geq 0 \quad \text{and integer} \tag{10}$$

$$r_t \geq \alpha x_t^R \quad \text{and integer} \tag{11}$$

Inventory capacities must be respected.

$$x_t^R \leq \kappa^{aR} \tag{12}$$

$$x_t^S \leq \kappa^S \tag{13}$$

The number of emissions to trade must be an integer and less than the maximum permitted. Moreover, the set of constraints (16) to (17) ensures it is possible to sell allowances only when the emissions from the previous period were reduced at least by β. The parameter β denotes the minimal reduction of emissions and M is a large positive constant.

$$C_t^+ \leq \kappa^e \tag{14}$$

$$C_t^- \leq \kappa^e y \tag{15}$$

$$\frac{\varpi_t - \varpi_{t+1}}{\varpi_t} \geq \beta + M(y-1) \tag{16}$$

$$y \geq 0, y \leq 1 \quad \text{and integer} \tag{17}$$

$$C_t^+, C_t^- \geq 0 \quad \text{and integer} \tag{18}$$

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

$$e_t \leq E^c \tag{19}$$

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

$$x_t^R \geq 0, e_t \geq 0 \tag{20}$$

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 characterization.

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 (6). 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 (6) and (7), 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 (6)). We repeat the proposed approach by permuting underlying environmental parameters (the emission cap, the allowance price) and the manufacturing cost.

5. Experimentation

The inventory model developed previously can be applied to any system as long as it possesses the characteristics described in Section 3. Based on our research objective, we chose to illustrate the applicability of the model and the proposed approach using the following numerical example.

5.1. Numerical Example

As shown in Table 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. For instance, in the electrical and electronic industry reverse logistics account for up to 80% of the total cost (Geyer and Blass, 2010), but as research advances, the economic performance is expected to improve (Low et al., 2014; Kilic et al., 2015). Moreover, in the particular sector of appliances and the automotive industry, producers are also revising product design to facilitate disassembly and reduce recycling fees (Kumar and Putnam, 2008; Xia et al., 2015).

The values used in the basic scenario are presented in Table 2. The original values are multiples of 10 in principle, rounded off to reduce the solution and state space, which would otherwise affect the resolution time significantly.

Table 2: Cost and emission factors

Parameter	Value	Parameter	Value
C_p	\$90/tonnes	C_c^+	\$1.36/tCO_2
C_r	\$130/tonne	C_c^-	\$1.32/tCO_2
C_d	\$0/tonne	e^p	2tCO_2/tonne
h_S	\$15/tonne	e^r	1tCO_2/tonne
h_R	\$1.6/tonne	E^c	8tCO_2
v	\$ 115/tonne	κ^e	2tCO_2
C_{ls}	\$179/tonne	α	0.1
β	0.2		

The production of aluminum is an energy-intensive process and consequently; it is frequently subject to environmental targets (Hong et al., 2012). Given the importance of the aluminum sector, we considered data on this 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) helped 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 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:

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

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

Table 3: Parameters

Parameter	Value
κ^p	50 tonnes
κ^r	20 tonnes
κ^S	8 tonnes
κ^{aR}	4 tonnes
κ^v	1 tonne

To characterize the cap and trade scheme our numerical examples relied on the literature and on legislation introduced by France and the state of California in the U.S. where the government sets a floor carbon price (California Air Resources Board, 2014). In 2016, California sold carbon credits at a minimum price of \$12.73/tCO_2, and for 2017 France established a floor price of \$33.95/tCO_2. Therefore, we decided to study allowance prices as low as \$13.6/tCO_2 to simulate current prices and prices as high as \$1002.00/tCO_2 to characterize the forthcoming years. Considering the production cost and the allowance price 20 scenarios were created. These scenarios were repeated for each emission cap tested. Table 4 summarizes the parameters (on multiples of 10) used for each scenario.

Table 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

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.

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 $\bar{q}^a$ is manufactured. Otherwise, no manufactured is required. Decisions resulting from the above policy are summarized as follows:

$$r_t = \lceil \alpha x_t^R \rceil \tag{21}$$

$$p_t = \begin{cases} \min\{\bar{q}^a - r_t, S^a - x_t^S - r_t\}, & x_t^S + r_t < S^a \\ 0, & \text{otherwise} \end{cases} \quad (22)$$

In this scenario, the parameter values corresponds to $S^a = 9$ and $\bar{q}^a = 7$. Using Expressions (6) and (7) respectively, the optimal cost of the baseline scenario is \$589.41 with an environmental impact of 7.6tCO_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 6.65tCO_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:

$$r_t = \begin{cases} \min\{x_t^R, \bar{q}^b\}, & x_t^S < S^b, \quad S^b - x_t^S \geq \bar{q}^b \\ \min\{x_t^R, S^b - x_t^S\}, & x_t^S < S^b \\ 0, & \text{otherwise} \end{cases} \quad (23)$$

$$p_t = \begin{cases} \bar{q}^b - r_t & x_t^S + r_t < S^b, \quad S^b - x_t^S \geq \bar{q}^b \\ S^b - x_t^S - r_t, & x_t^S + r_t < S^b \\ 0, & \text{otherwise} \end{cases} \quad (24)$$

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.

5.3. Inventory Control under Carbon Emissions Constraints

In the following, we evaluate the effect of using the inventory policies determined in section 5.2 in a system under carbon emission constraints.

We evaluate the impact on the total cost of the system. We tested four different emission cap values (E^c=2tCO_2, 3tCO_2, 4tCO_2, 5tCO_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.

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 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$.

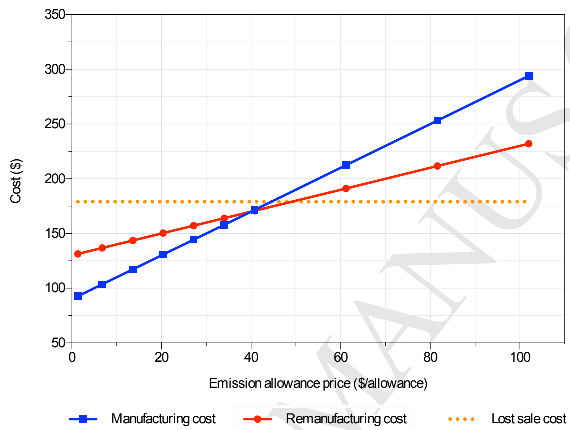

Figure 4: Relation between operational costs Case I

Figure 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.

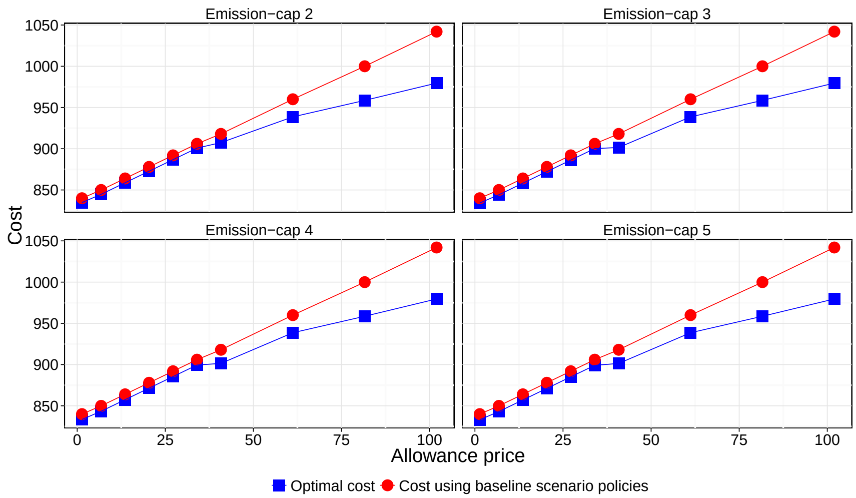

Figure 5: Deviation from optimal cost using baseline policies under cap-and-trade in case I

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

490 *5.3.2. Case II. Remanufacturing is less expensive and greener than manufacturing*

Figure 6 shows the increase in manufacturing and remanufacturing cost along with the allowance price. Manufacturing is always more expensive than remanufacturing.

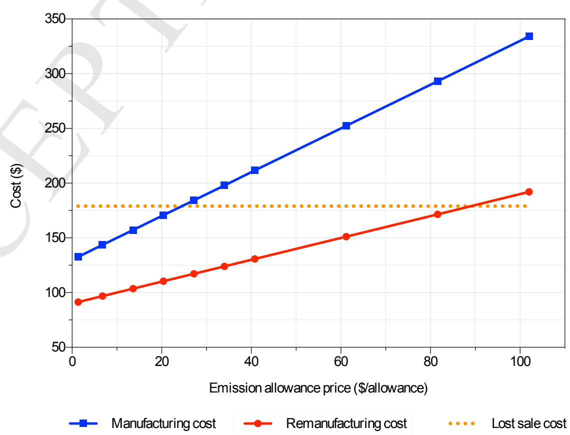

Figure 6: Relation between operational costs Case II

As it can be seen in Figure 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.

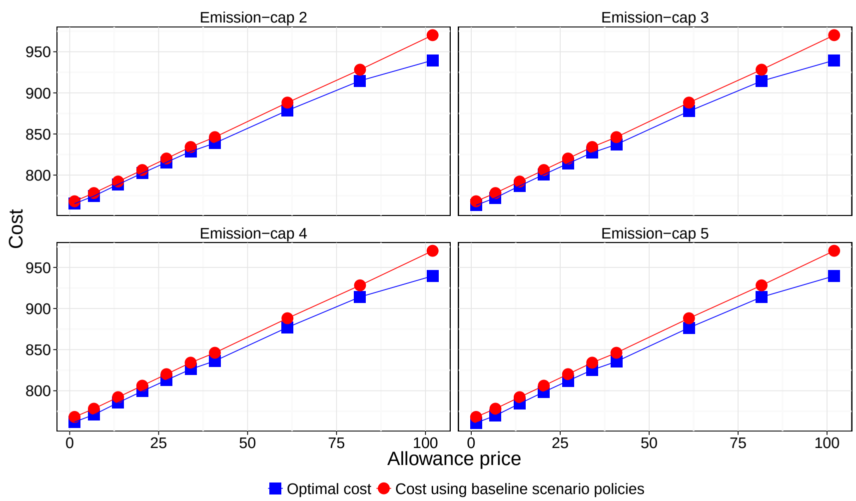

Figure 7: Deviation from optimal cost using baseline policies under cap-and-trade in case II

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 legislation. As for the previous experiments, we propose to analyze the inventory policies in the two cases.

In order to analyze the decisions, we derived classification trees using the CART algorithm implemented on Tree, a R package written by Ripley (2016). Our classification trees achieved an accuracy on average of 92.62% with a standard deviation of 5.31, the classification error obtained is associated with the complexity of the decisions. Although the structure of decision trees may depend on the data used, we gained visibility on decisions, so we derived general insights on decision-making. For instance, classification trees on the carbon sale strategy have a high accuracy since decisions are in the majority not to sell, and they are mainly in function of the carbon price. On the other hand, the decision trees associated with remanufacturing planning are more complex since the decisions depend on multiple states and parameters.

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

Figure 8 shows the classification tree for manufacturing. The remanufacturable inventory level and the number of emissions held 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.

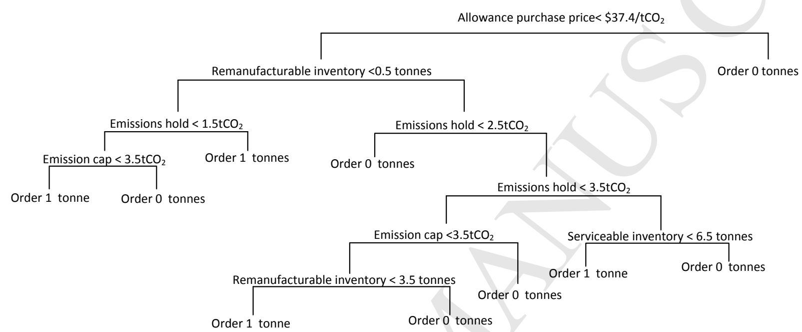

Figure 8: Classification tree of manufacturing strategy in case I. Classification error= 9.59%

Figure 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.

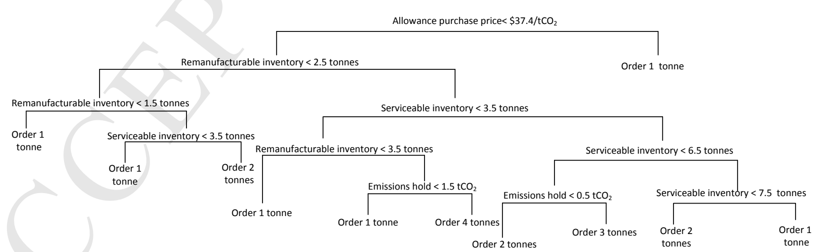

Figure 9: Classification tree of remanufacturing strategy in case I. Classification error= 9.84%

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 (ε'). 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 (ε'), under which remanufacturing is only used to guarantee the minimal remanufacturing proportion α. Hence,

$$
\begin{aligned}
r_t &= \lceil \alpha x_t^R \rceil && (25)\\
p_t &= 0 && (26)
\end{aligned}
$$

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 ε, ε 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 ε 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 α (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 κ^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:

$$
r_t = \begin{cases}
\min\{x_t^R, \bar{q}^c\}, & x_t^S < S^c, S^c - x_t^S \geq \bar{q}^c, e_t < E^c \\
x_t^R, & x_t^S < S^c, S^c - x_t^S \geq \bar{q}^c, e_t \geq E^c \\
\min\{x_t^R, S^c - x_t^S\}, & x_t^S + \varepsilon < S^c \\
\varepsilon, & \text{otherwise}
\end{cases} \quad (27)
$$

$$
p_t = \begin{cases}
\bar{q}^c - r_t, & x_t^S + r_t < S^c, S^c - x_t^S \geq \bar{q}^c, e_t < E^c \\
\bar{q}^c, & x_t^S + r_t < S^c, S^c - x_t^S \geq \bar{q}^c, e_t \geq E^c, \chi \geq \bar{q}^c \\
\min\{\lfloor \chi \rfloor, S^c - x_t^S - r_t\}, & x_t^S + r_t < S^c \\
0, & \text{otherwise}
\end{cases} \quad (28)
$$

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.

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 10 and 11 illustrates the classification trees for manufacturing and remanufacturing, respectively.

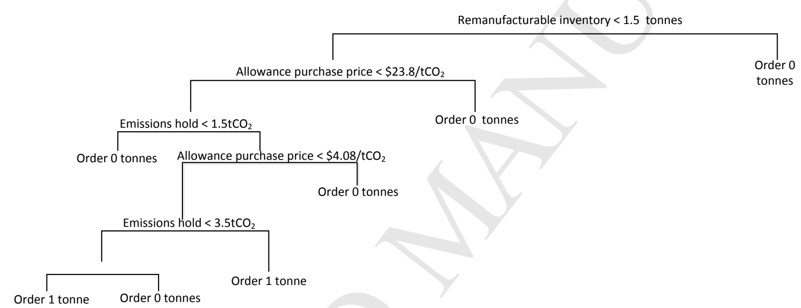

Figure 10: Classification tree of manufacturing strategy in case II. Classification error= 1.34%

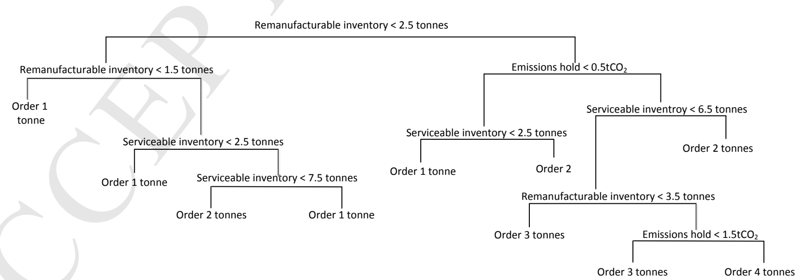

Figure 11: Classification tree of remanufacturing strategy in case II. Classification error= 16.74%

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 (ε'), characterize the second case, in which remanufacturing is cheaper than manufacturing.

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 ε 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 ε is greater than $S^e - x_t^S$, ε 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:

$$r_t = \begin{cases} x_t^R, & x_t^S < s^d, x_t^R \geq r^d \\ \min\{x_t^R, S^d - x_t^S\}, & x_t^S \geq s^d, \varepsilon < S^d - x_t^s \\ \varepsilon, & \text{otherwise} \end{cases} \tag{29}$$

$$p_t = \begin{cases} [\bar{q}^d - r_t]^+, & e_t \geq E^c - 1 \\ 0, & \text{otherwise} \end{cases} \tag{30}$$

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

The (ε') policy is the same as in the case I, in which only the minimal proportion α 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.

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.

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 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.

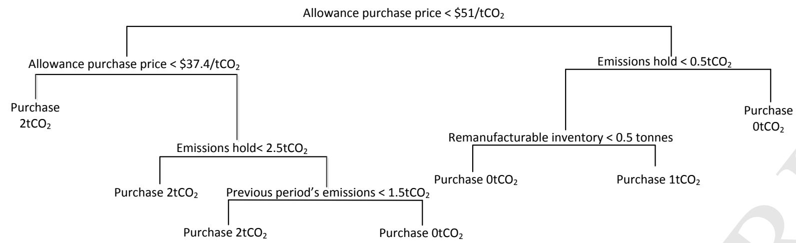

Figure 12: Classification tree of allowance purchase strategy in case I. Classification error= 9.59%

Figure 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.

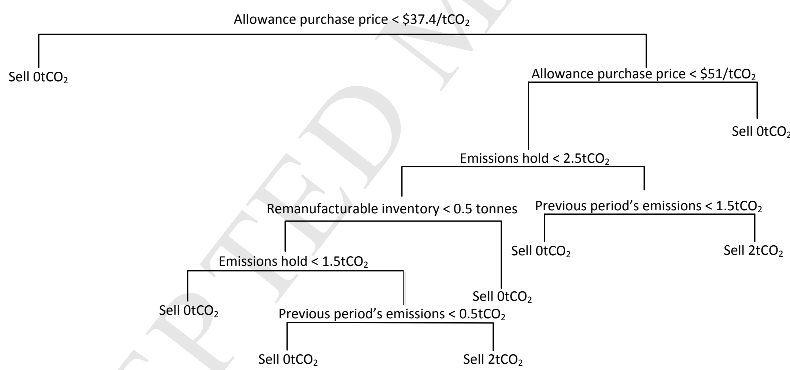

Figure 13: Classification tree of allowance sale strategy in case I. Classification error= 0.67%

5.5.2. Case II. Remanufacturing is less expensive and greener than manufacturing

Figure 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.

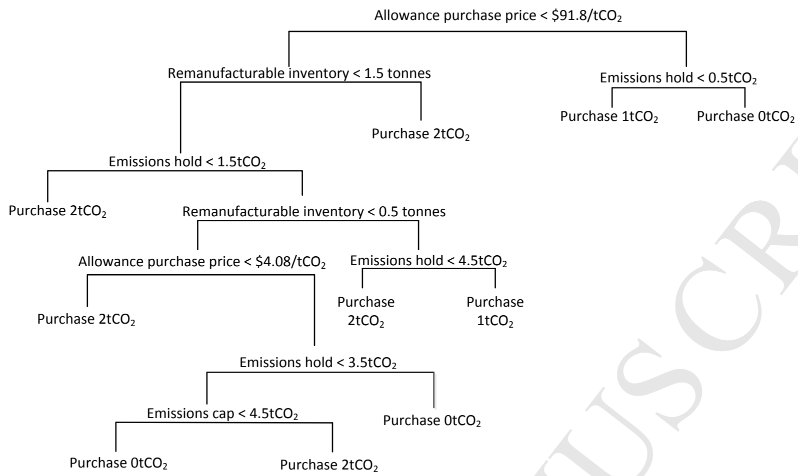

Figure 14: Classification tree of allowance purchase strategy in case II. Classification error= 9.78%

Figure15 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 to remanufacture is low and when the profit from the sale of allowances excesses the cost of using manufacturing.

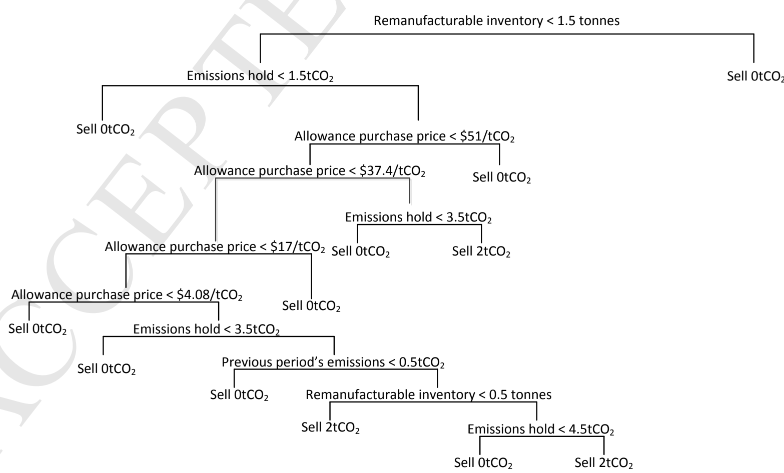

Figure 15: Classification tree of allowance sale strategy in case II. Classification error= 1.46%

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.

6.1. Managerial insights on the structure of inventory and carbon management policies

Results are summarized in Tables A.1 to A.4 in Appendix A. 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 5.4.1 and 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 average deviation from the optimal cost (column 8) when the policy in column 6 is applied.

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

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.

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.

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.

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 $\$40/tCO_2$. If the environmental impact of each process is considered, remanufacturing is cheaper than manufacturing at $\$40/tCO_2$. Moreover, when the carbon price is higher than $\$44.50/tCO_2$, the manufacturing cost exceeds the cost of lost sales.

When the carbon price is increased up to \$50tCO_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 ϵ' policies exist and why the former (which uses manufacturing and remanufacturing) is applicable when the carbon price is below \$40/tCO_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/tCO_2.

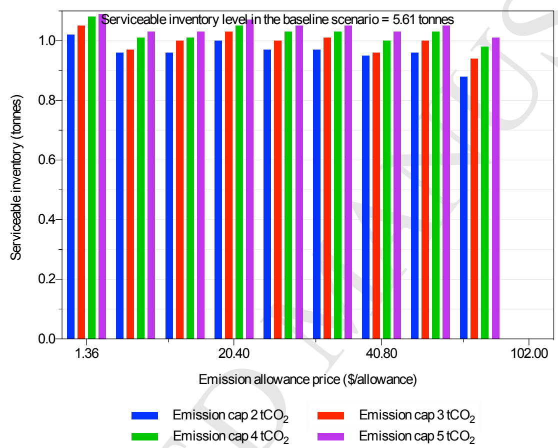

Figure 16: Expected serviceable inventory per scenario Case I

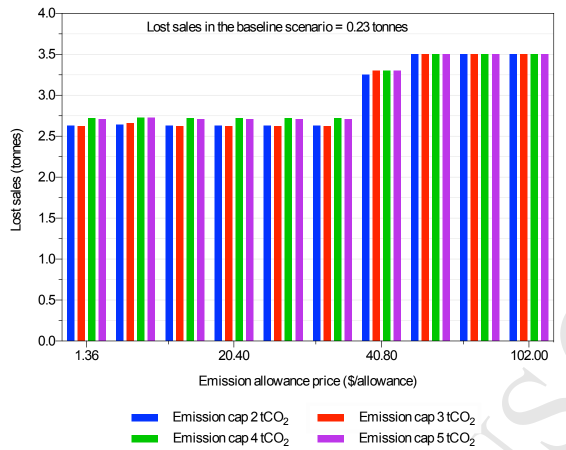

Figure 17: Expected lost sales per scenario Case I

The existence of the threshold price affects all decisions and the state of the system. While manufacturing is ongoing, the serviceable inventory (Figure 16) is full most of the time, then assuring a high service level (Figure 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 18). In this situation, it would be advisable to make strategic decisions such as low-carbon technology investments.

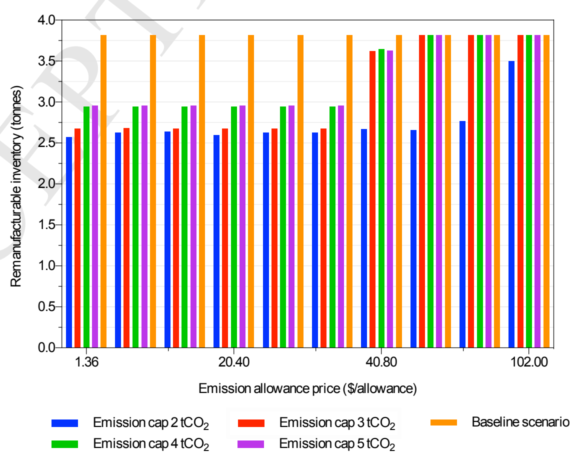

Figure 18: Expected remanufacturable inventory per scenario Case I

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/tCO_2. Manufacturing is stopped when the allowance price reaches \$24.5/tCO_2, and remanufacturing stops when the prices exceeded \$89/tCO_2.

Contrary to case I, in case II remanufacturing is stopped at a higher allowance price. Then, we observed a higher serviceable inventory (Figure 19) and service level (Figure 20 for a longer interval of allowance prices.

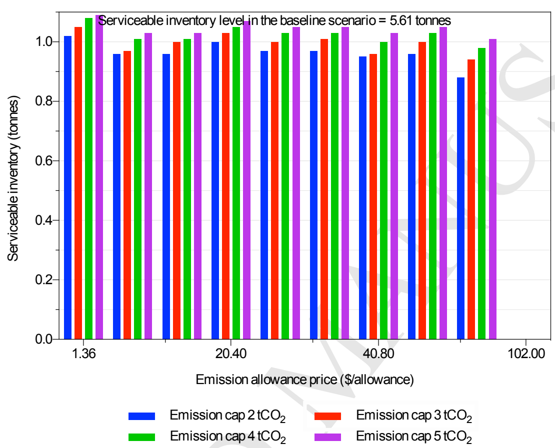

Figure 19: Expected serviceable inventory in case II

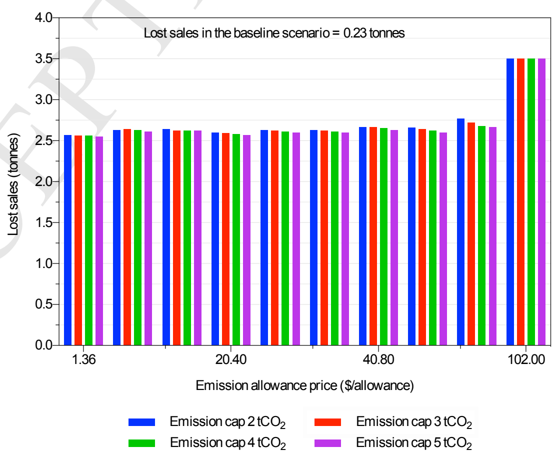

Figure 20: Expected lost sales per scenario in case II

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

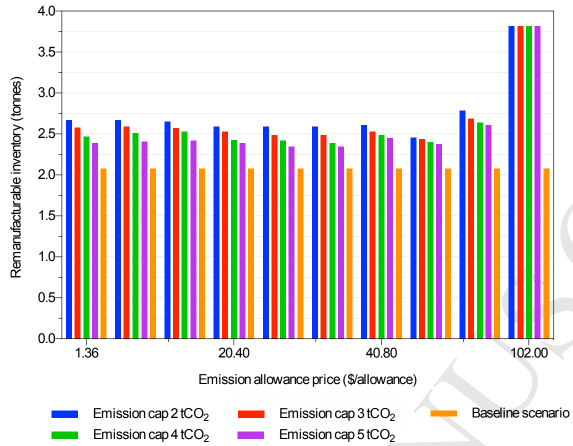

Figure 21: Expected remanufacturable inventory per scenario Case II

6.3. Impact of the Emission Cap on Decisions

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.

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 22), a reduction of $5.64tCO_2$ was achieved in all instances. In case II (Figure 23), the reduction averaged $4.73tCO_2$ with a standard deviation of 0.03. On the other hand, we note that emissions were $2tCO_2$ in case I and $1.92tCO_2$ 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.

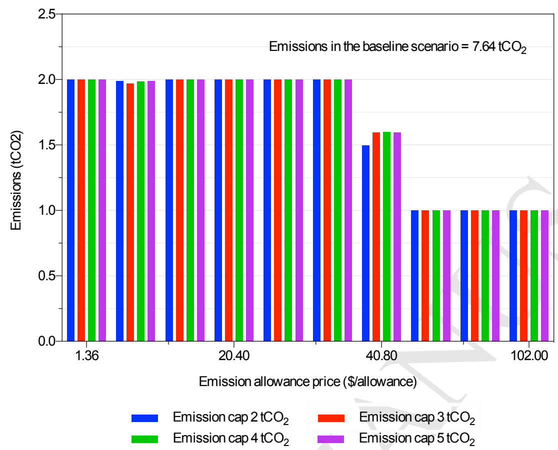

Figure 22: Expected emissions (tCO_2) per scenario Case I

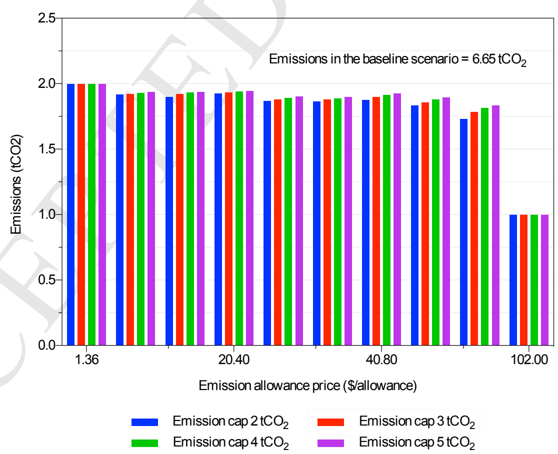

Figure 23: Expected emissions (tCO_2) per scenario Case II

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

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.

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 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 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.

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Appendix A.

Table A.1: 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	(ε')	-	938.61	1.00	0.00
9	90	130	81.60	79.15	2	(ε')	-	958.60	1.00	0.00
10	90	130	102.00	98.94	2	(ε')	-	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	(ε')	-	939.61	1.00	0.00

Table A.2: 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	(ε')	-	901.51	1.60	1.23
8	90	130	61.20	59.36	3	(ε')	-	938.61	1.00	0.00
9	90	130	81.60	79.15	3	(ε')	-	958.60	1.00	0.00
10	90	130	102.00	98.94	3	(ε')	-	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	(ε')	-	939.61	1.00	0.00

Table A.3: 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	(ε')	-	938.61	1.00	0.00
9	90	130	81.60	79.15	4	(ε')	-	958.60	1.00	0.00
10	90	130	102.00	98.94	4	(ε')	-	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	(ε')	-	939.61	1.00	0.00

Table A.4: 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	(ε')	-	901.42	1.60	1.09
8	90	130	61.20	59.36	5	(ε')	-	938.61	1.00	0.00
9	90	130	81.60	79.15	5	(ε')	-	958.60	1.00	0.00
10	90	130	102.00	98.94	5	(ε')	-	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	(ε')	-	939.61	1.00	0.00

Highlights

- This study aims to define the effect of a cap-and-trade scheme on inventory control.
- Managerial insights into the structure of green inventory policies are given.
- Restructuring inventory policies is helpful to meet a cap-and-trade strategy.
- Carbon credit prices have a significant effect on decisions.
- There is a critical carbon price beyond which strategic decisions must be made.