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Joint strategic and tactical planning under the dynamics of a cap-and-trade scheme

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Abstract: This paper explores how environmental investments, capacity expansion and production and inventory planning interact to comply with a cap-and-trade mechanism. We consider a supply chain system subject to a cap-and-trade regulation. 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, its capacity can be increased throughout the planning horizon. It is also possible to cut the total carbon footprint by investments in emission control technologies. Decisions are then made on how best to invest in carbon abatement strategies, capacity sizing, and production and carbon management planning to meet a cap-and-trade scheme over time. 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 characterize strategic and tactical decisions and perform 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. In particular, our results show if the allowance price is beyond a threshold value, investments are critical to the economic survival of a firm.

Keywords: Cap-and-trade, Paper mill, Sustainable supply chain

1. INTRODUCTION

The cap-and-trade system is an environmental policy that promotes the reduction of greenhouse gasses (GHG) emissions. Under this program, regulated companies must hold enough carbon credits (allowances) for cover their GHG emissions. To comply the law, companies may reduce their emissions or sell and buy emission allowances on the carbon market. Each year, the policy is expected to be more rigorous as allowances would be more expensive, and their availability would be reduced. The mandatory nature of the policy and the eminently tightening of legislation makes imperative to address the integration of the cap-and-trade in industries.

According to the findings of García-Alvarado et al. (2015) existing management strategies cannot accomplish to curb carbon emissions without sacrificing the profit. Though, changes to the production plan and the inventory strategy can yield to significant GHG savings without greatly increasing the cost. Clearly, there are limits to which tactical decisions can help to achieve environmental gains (García-Alvarado et al., 2015). As the allowance prices increase, and the emission-cap tightens the system struggle to reduce the carbon footprint and sales are lost. At this state, García-Alvarado et al. (2015) motivate to focus on strategic and tactical decisions to build supply chains that are both cost-effective and environmentally-friendly. Motivated by this, our main interest is to determine under which circumstances, capacity expansion, strategic investments as byproducts' treatment, and production-inventory planning help satisfy the new environmental constraints without significantly reducing the total profit.

2. THE CAP-AND-TRADE REGULATION AND LITERATURE REVIEW

2.1 California's cap-and-trade

California's cap-and-trade is a legislation meant to control the number of emissions generated. Each year, covered entities are required to give an allowance for each tCO_2e generated.

The cap-and-trade program is composed of three compliance periods 1) 2013-2014, 2) 2015-2017, 3) 2018-2020. The dynamics of the system are the following: At the beginning of each year, 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.

The annual allocation of free allowances relies mostly on the industry leakage risk and the sector. Covered industries are classified in three groups according to their leakage risk: 1) high, 2) medium, and 3) low. The leakage risk would determine the assistance factor that is the fraction of allowances freely granted by the government to help

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industries. Other factors such as the cap adjustment and the emission efficiency benchmark depend on the sector. The cap adjustment factor indicates the tightening of the emission-cap. The emission efficiency benchmark is used to evaluate GHG emission efficiency between and among processes in the same industrial sector.

Companies that have exceeded their emission-cap or have surplus allowances may buy or sell allowances to comply with the legislation. Emissions can be purchased or sold on the carbon market during auctions held at quarterly intervals. The price paid by bidders is mainly market-driven, although the government also set a floor allowance price. Each covered entity possesses two types of accounts to bank their allowances, namely the compliance account and the holding account. The former holds the allowances to meet the requirements of the program. Allowances translated into this account cannot be transferred elsewhere. In contrast, the holding account permit companies to bank their allowances, and they can be sold or traded.

2.2 Related literature

Studies that explore the role of environmental investments include the work of 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. (2014) considered a technology choice and capacity investment problem under a cap-and-trade scheme for a single period make-to-order context. Their results support that high taxes will decrease investments in cleaner technology.

Among the published studies on production planning and inventory control, the work of Subramanian et al. (2007) focused on investment strategies under emission trading. They found that the number of available permits affects emission abatement levels. Gong and Zhou (2013) presented a multi-period production planning subject to a cap-and-trade scheme. They 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 the traditional. 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. Later on, Fahimnia et al. (2015) characterized production and allocation strategies for a carbon tax scheme. They determined insights into the carbon pricing strategy. Zkeri et al. (2015) presented a supply chain planning model subject to carbon tax and emission trading. They argued that under a cap-and-trade scheme the supply chain performance in terms of carbon footprint and 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 on 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.

Within the literature that considers strategic and tactical decisions under ecological concerns, the work of Chaabane et al. (2012) studied a supply chain network subject to a cap-and-trade scheme. Their results support that carbon management strategies aid to achieve sustainability targets. 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. 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. They affirmed that the profit can be increased when environmental investments are made.

Even though the existing literature has examined several aspects of the cap-and-trade scheme, to our knowledge, no study has integrated 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 literature and the cap-and-trade scheme. Further, we explore how environmental investment and capacity design maximize the profit while minimizing the carbon footprint of a firm.

3. PROBLEM DESCRIPTION AND MATHEMATICAL MODEL FORMULATION

3.1 Problem description

We considered a finite-horizon single-product supply chain subject to a cap-and-trade scheme. The system consists of two production facilities namely manufacturing and remanufacturing. The production capacity of remanufacturing can be increased over the 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 production facilities and stocking points are already established. Decisions, therefore, are only focused at the strategic level on environmental project investments, capacity sizing, sales, and production/inventory planning, and at the tactical level on carbon management strategies.

The planning horizon is composed of a set $\mathcal{M}$ 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 denotes the end of a three-year period. Meanwhile, regular periods refer to the periods comprised in a three-year interval. We define the set of closing period as $\mathcal{J} \subset \mathcal{M}$.

Under the cap-and-trade, at the beginning of each year $m \in \mathcal{M}$ an amount α_m of allowances are freely granted to the system. This quantity depends on the adjustment factor ϵ_m, the assistance factor β_m and the carbon emissions benchmark $\bar{e}$. During regular annual periods $m \in \mathcal{M} \setminus \mathcal{J}$, a minimal percent ($\tau_m$) of the previous year emissions has to be covered with allowances. During closing compliance periods $j = 1, ..., J$, there is no annual obligation but a triennial obligation. The sum of uncovered emissions during the years of the compliance period have to be surrendered. The compliance account level (C_m) must be hold the number of emissions required at each year. If a company excesses the freely allocated emissions or has an excess of allowances, carbon allowances can be bought and sold during auction periods held quarterly per year. We define a set $\mathcal{N}$ of auction periods $n = 1, ..., N$ quarterly distributed during 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 emission ($S_{m,n}$) 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 have to be bought and sold in multiples of 1,000, and there is an allowance purchase/sale limit ($g_{m,n}$) at each auction. It is possible to bank carbon allowances at the holding account (H_m) from period to period as long as the holding limit (h_m) is not surpassed.

We considered annual demand (χ_m) as independent random variables and follows a known discrete distribution function with a probability distribution $\phi(\delta_m) = \Pr[\chi_m = \delta_m]$. Demand can be satisfied by two processes, namely manufacturing and remanufacturing. Both technologies incur an environmental impact denoted by e (q) and a cost y (x) per unit, respectively. We assume $q < e$ and $y > x$. Remanufacturing requires recovered material to produce. Returns are held in the remanufacturable stocking point (Z_m), and there is a holding cost (μ) associated with the average inventory level during each period. We considered the quality of end-of-life products is stable and with market surplus. Then, we assumed the acquisition of recovered products as deterministic. Meanwhile, manufacturing requires virgin raw material to produce. Virgin material is held in the stocking point R_m; and at the end of periods the average inventory level incurs in a holding cost σ. Both technologies manufacture same quality products. Replenishment orders arrive with zero lead-time at the serviceable stocking point (V_m), where a holding cost (γ) is incurred by the average inventory level during each period. Demand is satisfied from the serviceable inventory.

To reduce the carbon footprint is possible to expand the capacity of remanufacturing by J_m increments at a variable cost κ and a fixed cost d. Albeit, capacity cannot exceed a maximum $\bar{k}$. It is also possible to gain allowances (environmental reward) by making investments in emission abatement technology. We assumed the environmental reward to be a piecewise linear function of the investments made. We define a set of segments $\mathcal{I}$ with $i = 1, ..., I$ to characterize the slope changes.

3.2 Sequence of events

The sequence of events is as follows: At the beginning of each compliance period $m \in \mathcal{M}$, remanufacturing capacity expansion, and environmental project investments $i \in \mathcal{I}$ are reviewed and made if applicable. Capacity expansion, and project investments' benefits arrive instantly during period $m \in \mathcal{M}$. At the beginning of annual compliance periods, inventory levels are reviewed and manufacturing and remanufacturing orders are placed. Afterwards, the decision-maker determines replenishment quantities from each technology. Demand is next incurred. Sales are made based on the available serviceable inventory. We assume 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 purchase and sale instantly occurs.

3.3 Notation

Decision variables

Δ_m:	Carbon footprint of period $m \in \mathcal{M}$.
Υ_m	Quantity of allowances surrendered during period $m \in \mathcal{M}$.
Λ_m:	Allowances transferred to the compliance account during period $m \in \mathcal{M}$.
Y_m:	Quantity manufactured during period $m \in \mathcal{M}$.
X_m:	Quantity remanufactured during period $m \in \mathcal{M}$.
Π_i:	1 if abatement rate $i \in \mathcal{I}$ is used; 0 otherwise.
$F_{m,i}$:	Investment made at rate $i \in \mathcal{I}$ during period $m \in \mathcal{M}$.
K_m:	Capacity of remanufacturing during period $m \in \mathcal{M}$.
D_m:	1 if remanufacturing capacity is expanded during period $m \in \mathcal{M}$; 0 otherwise.
L_m:	Lost sales during period $m \in \mathcal{M}$.
Θ_m:	Virgin material required during period $m \in \mathcal{M}$.
Ω_m:	Recovered material required during period $m \in \mathcal{M}$.
A:	Total carbon footprint over the whole planning horizon.
ψ:	Fill rate.

Parameters

w_i:	Carbon reduction rate at $i \in \mathcal{I}$.
β_m:	Industry assistance factor during period $m \in \mathcal{M}$.
o_m:	Initial period for compliance period ending during year $m \in \mathcal{J}$.
$\bar{c}$:	Final compliance account level.
$\bar{h}$:	Final holding account level.
$\bar{g}$:	Allowance batch size (1,000 allowances).
p:	Retail price per unit.
ν:	Lost sale price per unit.
θ:	Acquisition cost per unit of virgin raw material.
ω:	Acquisition cost per unit of recovered material.
λ	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.
k	Discount rate.
ς_i:	Length of segment $i \in \mathcal{I}$.

3.4 Objective function and constraints

The objective function (1) to be maximized is the total discounted profit calculated as follows:

$$\max \underbrace{\sum_{m \in \mathcal{M}} \left(\frac{1}{1+k}\right)^m (p(\delta_m - L_m) - \nu L_m)}_{\text{sales revenue}}$$

$$+ \underbrace{\sum_{n \in \mathcal{N}} \sum_{m \in \mathcal{M}} \left(\frac{1}{1+k}\right)^m (s_{m,n} S_{m,n})}_{\text{emission trading revenue}}$$

$$- \underbrace{\sum_{n \in \mathcal{N}} \sum_{m \in \mathcal{M}} \sum_{m' \in \mathcal{M}} \left(\frac{1}{1+k}\right)^m \left(b_{m,n} B_{m,n,m'}\right)}_{\text{emission trading cost}}$$

$$- \underbrace{\sum_{m \in \mathcal{M}} \sum_{i \in \mathcal{I}} \left(\frac{1}{1+k}\right)^m F_{m,i}}_{\text{investment cost}} - \underbrace{\sum_{m \in \mathcal{M}} \left(\frac{1}{1+k}\right)^m (dD_m + \kappa J_m)}_{\text{capacity expansion}}$$

$$- \underbrace{\sum_{m \in \mathcal{M}} \left(\frac{1}{1+k}\right)^m (\theta \Theta_m + \omega \Omega_m)}_{\text{raw material acquisition cost}}$$

$$- \underbrace{\sum_{m \in \mathcal{M}} \left(\frac{1}{1+k}\right)^m (yY_m + xX_m)}_{\text{production cost}}$$

$$- \underbrace{\sum_{m\in\mathcal{M}} \left(\frac{1}{1+k}\right)^m \left(\gamma\bar{V}_m + \mu\bar{U}_m + \sigma\bar{R}_m\right)}_{\text{inventory holding cost}} \quad (1)$$

The above function is subject to the following set of constraints:

Environmental constraints The number of allowances freely granted to the system is given by Expression (2).

$$\beta_m \epsilon_m \bar{e}\,(Y_{m-2} + X_{m-2}) \geq \alpha_m \qquad \forall m \in \mathcal{M} \quad (2)$$

The carbon footprint at each period, Expression (3), is calculated in function of the carbon emissions generated by the quantities produced.

$$\Delta_m = (eY_m + qX_m) \qquad \forall m \in \mathcal{M} \quad (3)$$

The quantity of allowances to be surrendered must be greater than the minimal requirement given by Expression (4). Moreover, the quantity to submit cannot exceed the previous year's emissions, Expression (5).

$$\Upsilon_m \geq \tau_m \Delta_{m-1} \qquad \forall m \in \mathcal{M} \setminus \mathcal{J} \quad (4)$$

$$\Upsilon_m \leq \Delta_{m-1} \qquad \forall m \in \mathcal{M} \setminus \mathcal{J} \quad (5)$$

For closing periods, the number of allowances to submit is the sum of the non-surrendered allowances during the three-year period.

$$\Upsilon_m = \sum_{\substack{l\in\mathcal{M} \\ o_m \leq l \leq m-1}} \Delta_l - \sum_{\substack{l\in\mathcal{M} \\ o_m+1 \leq l \leq m-1}} \Upsilon_l \qquad \forall m \in \mathcal{J} \quad (6)$$

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.

$$\Upsilon_M = \sum_{\substack{l\in\mathcal{M} \\ o_M \leq l \leq M}} \Delta_l - \sum_{\substack{l\in\mathcal{M} \\ o_M+1 \leq l \leq M-1}} \Upsilon_l \qquad \forall m \in \mathcal{J} \quad (7)$$

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.

$$C_m = C_{m-1} + \Lambda_m - \Upsilon_m \qquad \forall m \in \mathcal{M} \quad (8)$$

The number of allowances held during each period 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 and sold.

$$H_m = \alpha_m + H_{m-1} - \Lambda_m + \sum_{i\in\mathcal{I}} (w_i F_{m,i}) - \sum_{n\in\mathcal{N}} (\bar{g} S_{n,m}) + \sum_{n\in\mathcal{N}} \sum_{\substack{m'\in\mathcal{M} \\ m' \leq m}} (\bar{g} B_{m',n,m}) \qquad \forall m \in \mathcal{M} \quad (9)$$

The amount of allowances banked at each period must be less than or equal to the maximum allowance holding.

$$H_m \leq h_m \qquad \forall m \in \mathcal{M} \quad (10)$$

The amount of allowances purchased cannot exceed a maximum quantity.

$$B_{m,n,m'} \leq g_{m,m'} \qquad \forall m, m' \in \mathcal{M}, \forall n \in \mathcal{N} \quad (11)$$

To avoid, emptying the system there a minimal number of allowances to hold at the end of the horizon.

$$C_M \geq \bar{c} \quad (12)$$

$$H_M \geq \bar{h} \quad (13)$$

Investment constraints Conditional constraints for each segment of the investment curve are given by Expressions (14) and (15).

$$\sum_{m\in\mathcal{M}} F_{m,i} \leq \varsigma_i \Pi_{i-1} \qquad \forall i \in \mathcal{I} \quad (14)$$

$$\sum_{m\in\mathcal{M}} F_{m,i} \geq \varsigma_i \Pi_i \qquad \forall i \in \mathcal{I} \quad (15)$$

Inventory balance constraints The remanufacturable, virgin raw material, and serviceable inventory balances are given by Expressions (16) to (18), respectively.

$$R_m = R_{m-1} - Y_m + \Theta_m \qquad \forall m \in \mathcal{M} \quad (16)$$

$$U_m = U_{m-1} - X_m + \Omega_m \qquad \forall m \in \mathcal{M} \quad (17)$$

$$V_m = V_{m-1} + Y_m + X_m + L_m - \delta_m \qquad \forall m \in \mathcal{M} \quad (18)$$

The average inventories level for the three stocking points are computed in the following form:

$$\bar{R}_m = \frac{R_{m-1} + R_m}{2} \qquad \forall m \in \mathcal{M} \quad (19)$$

$$\bar{U}_m = \frac{U_{m-1} + U_m}{2} \qquad \forall m \in \mathcal{M} \quad (20)$$

$$\bar{V}_m = \frac{V_{m-1} + v_m}{2} \qquad \forall m \in \mathcal{M} \quad (21)$$

The final inventories must be greater than the minimal requirement.

$$R_M \geq \bar{r} \quad (22)$$

$$U_M \geq \bar{u} \quad (23)$$

$$V_M \geq \bar{v} \quad (24)$$

Capacity constraints and upper limits Remanufacturing capacity at each period depends on the previous' period capacity plus the expansions made formerly, Expression (25). Moreover, the capacity must not exceed a maximum level, Expression (26).

$$K_m = K_{m-1} + J_m \qquad \forall m \in \mathcal{M} \quad (25)$$

$$K_m \leq \bar{k} \qquad \forall m \in \mathcal{M} \quad (26)$$

Expression (27) is an auxilary constraint to consider if an expansion has been made, a fixed cost is incurred.

$$J_m \leq \bar{k} D_m \qquad \forall m \in \mathcal{M} \quad (27)$$

Processes' and holding capacities are defined by Expressions (28)- (31).

$$Y_{m,} \leq \lambda \qquad \forall m \in \mathcal{M} \quad (28)$$

$$X_m \leq K_m \qquad \forall m \in \mathcal{M} \quad (29)$$

$$V_m \leq v \qquad \forall m \in \mathcal{M} \quad (30)$$

$$U_m \leq u \qquad \forall m \in \mathcal{M} \quad (31)$$

$$R_m \leq r \qquad \forall m \in \mathcal{M} \quad (32)$$

Constraint (33) expresses upper limits on the amount of lost sales per period, lost sales cannot exceed demand during any period.

$$L_m \leq \delta_m \qquad \forall m \in \mathcal{M} \quad (33)$$

Non-negativity and integrity constraints Constraints (35) to (42) express the non-negativity and, if applicable, the integrity of the decision variables.

$$F_{m,i} \in \mathbb{R}_+, \qquad \forall m \in \mathcal{M}, \quad \forall i \in \mathcal{I} \quad (34)$$

$$Y_m, X_m, V_m, Z_m, H_m, L_m, K_m \in \mathbb{R}_+, \qquad \forall m \in \mathcal{M} \quad (35)$$

$$C_m, R_m, \Theta_m, \Omega_m, \bar{R}_m, \bar{U}_m, \bar{V}_m \in \mathbb{R}_+, \qquad \forall m \in \mathcal{M} \quad (36)$$

$$\Upsilon_m, \Lambda_m, \Delta_m \in \mathbb{R}_+, \qquad \forall m \in \mathcal{M} \quad (37)$$

$$\alpha_m, J_m \in \mathbb{Z}_+, \qquad \forall m \in \mathcal{M} \quad (38)$$

$$B_{m,n,m} \in \mathbb{Z}_+, \qquad \forall m, m' \in \mathcal{M}, \quad \forall n \in \mathcal{N} \quad (39)$$

$$S_{m,n} \in \mathbb{Z}_+, \qquad \forall m \in \mathcal{M}, \quad \forall n \in \mathcal{N} \quad (40)$$

$$D_m \in \{0,1\}, \qquad \forall m \in \mathcal{M} \quad (41)$$

$$\Pi_i \in \{0,1\}, \qquad \forall i \in \mathcal{I} \quad (42)$$

4. ILLUSTRATIVE EXAMPLE

We applied the above model to the pulp and paper industry. Yet, it can be extended to any other context as long as it shares the same characteristics discussed in section 3.

We considered two processes: Manufacturing which uses harvest forest as raw material, and remanufacturing, which transforms recovered paper into finished products. Since recycling involves extra processes such as sorting, and washing, we considered thus that remanufacturing is greener but more expensive than manufacturing.

We coded and solved the proposed model using Python and Gurobi as a solver. 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: 1) Scenario 1 (baseline problem) assumes that investments and capacity expansions are impossible, and 2) Scenario 2 (carbon abatement strategies) investigates the profitability of making investments in capacity expansion and pollution abatement technologies.

4.1 Data Sources

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.

We studied the compliance periods 2015-2033 (19 years), where we considered years 2015, 2018, 2021, 2024, 2027 and 2030 as initial and closing periods. In addition we studied allowance prices in the range [$20,$500] during the whole planning horizon, and assumed there is a loss when allowances are sold. Regarding annual allocation, we explored assistance factors in the interval [0%,100%]. Moreover, to represent the yearly decrease on freely allocation we used an adjustment factor of 2%. Furthermore, during regular years, at least 30% of the previous year's emissions must be surrendered.

4.2 Resutls

In the model presented in section 3, we measured the carbon footprint of the firm in terms of the environmental effect of the production processes. Then, in Scenario 1 there is no other strategy for carbon abatement but losing sales.

In general, the results indicate that investments and capacity expansion programs strengthen the economic benefit while reducing the carbon footprint. Figure 1 illustrates the profit for Scenario 1 and 2 under different allowance prices and assistance factors. When investments and capacity expansion are possible, the profit increases. As an illustrative example when the allowance price is set to $30/allowance, the profit is augmented in average 5.78%, equivalent to $165,128,000 over the whole planning horizon and $8,690,000 yearly. Production cost, raw material acquisition, and carbon trading account for the most difference in cost.

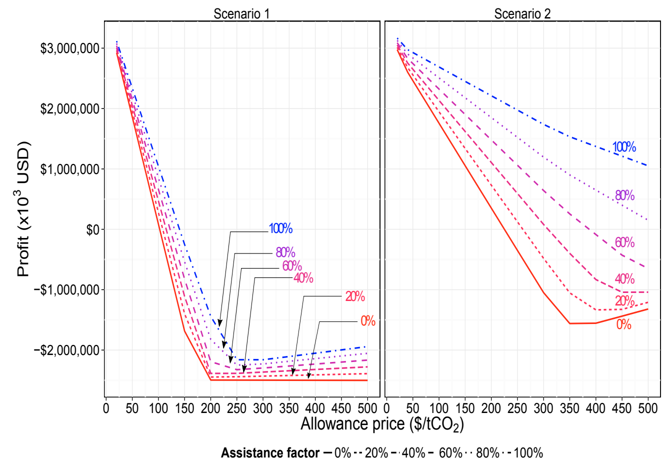

Fig. 1. Total profit under different parameter settings

At the same time, investment in carbon-reduction projects and capacity expansion strategies allows the shrinkage of carbon footprint levels. On average, when the allowance price is set to $30/allowance in Scenario 2, GHG levels are cut down by 52 % equivalent to 23 333 $MtCO_2$ over the whole planning horizon, and to 1 228 $MtCO_2$ per annum.

The effect of investments and capacity expansion can be further explored by analyzing the fill rate. Figure 2 illustrates the fill rate for the different scenarios and parameter settings. The 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

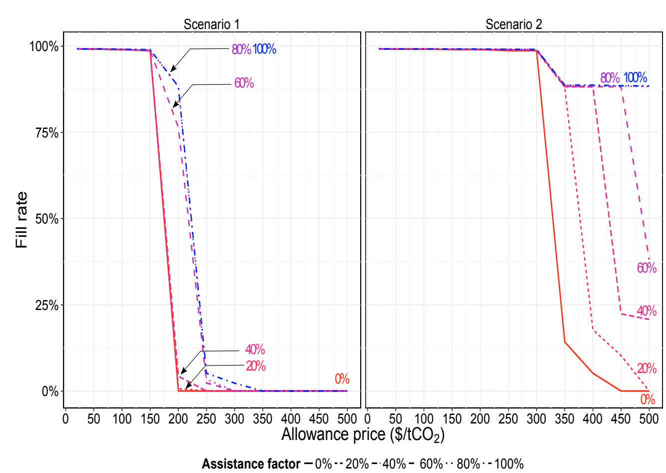

Fig. 2. Fill level under different parameter settings

analysis of the profit, carbon footprint, and fill rate, our results suggest a direct and an indirect correlation between the assistance factor and the allowance price with the total profit, respectively. The higher the allowance price, the lesser the profit. In Scenario 1, when the allowance price is greater or equal to $150/allowance, it is no longer profitable to satisfy the whole 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 higher than $300.

The maximal remanufacturing capacity expansion is made with allowance prices greater than $20/allowances regardless of the assistance factor. Regarding investments, higher allowance prices encourage stronger investments. We might differentiate two zones: 1) Low investment level (investments in average $6,000,000 equivalent to 7 200 $MtCO_2$); and 2) high investments (investments in average $10,000,000 equivalent to 12,000 $MtCO_2$). We may recall that in Scenario 1 the allowance price at which the marginal revenue equals the marginal cost is between $100 and $150. In Scenario 2, it is between the former range than investments are intensified. Then, investments would be triggered by the relation between allowance prices, marginal revenue, and investment costs.

5. DISCUSSION

Our results suggest carbon abatement faces limits when investments and capacity sizing are impossible. While production planning and inventory control decisions have already been aligned with environmental strategies, further emission reduction cannot be accomplished without compromising the economic performance of the system. Our findings indicate that an integrated approach provides a solution to the limits of tactical planning.

A joint strategic and tactical planning yields to an increase in earnings and a diminution of the carbon footprint of a firm subject to a cap-and-trade scheme. Cap-and-trade systems present the company with some uncertainty regarding carbon prices and availability. A joint approach help to counteract those effects.

Pricey carbon allowances reduce profit and tighter assistance factors cause environmental instability. Clearly, those factors do have an effect on strategic and tactical decisions. In particular, if the allowance price exceeds a threshold price, greater environmental investments would be preferred. On the other hand, assistance factors foster an environmental stability that may result in lower allowance purchase and additional gains from carbon sales.

Expensive allowances and low assistance factors encourages capacity expansion and investments on carbon reduction strategies. The fact that is possible to augment the capacity of the greenest process (remanufacturing) and make investments to curb emissions brings environmental stability to the system. An increased stability enables the firm to make steadier decisions regarding the number of allowances to purchase and the amount emissions to surrender.

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 the total profit. Clearly, the potential of investments and capacity expansion depends on several factors. In particular, our results gave evidence that pricey carbon allowances reduce profit while increasing investments. Meanwhile, higher assistance factors contribute to greater environmental stability that is reflected in lower carbon purchases and bigger profits.

Our study can be extended in further work. While it is foreseen a scenario in which allowance availability is uncertain, and their price might increase. 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 an extended analysis of its effects on decisions should be carried out.

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