The Emission Ordering Strategy with Green Awareness under the Emission Trading System (ETS)

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Abstract: Global concerns for environmental sustainability obligate manufacturers under the Emission Trading Scheme (ETS) to reduce carbon emission substantially. While green awareness inspires manufacturer investment in green upgrade, it is crucial for emission-limited firms to improve production scheduling in order to compete in the stringent low-carbon market. This paper solves the emission ordering problem by considering the green investment strategy. It adopts newsvendor models with novelty in the use of the Lagrange Multipliers and Karush-Kuhn-Tucker (KKT) conditions to achieve the optimality subject to emission constraints. Although this method has been used in economics, it is first explored in this paper for low-carbon production to achieve optimality together with the emission targets. The results call for the manufacturer to make better decisions for achieving both the optimality and the emission reduction.

1 INTRODUCTION

Carbon emission, allegedly the driver of global warming, has aroused much global concerns for sustainability. As the manufacturing industry weighs heavily on carbon emission (International Energy Agency, 2017), reducing its emission is key to achieving low-carbon development.

The Emission Trading System (ETS) is the first and remains the largest emission policy throughout the world. Under it, a manufacturing firm is endowed and hence capped with free emission credits, which can be traded with carbon emission price in the carbon market. Heavy-emitting firms with insufficient emission credits have to purchase credits or invest in the green upgrade (Xu et al., 2017), while greener firms can benefit from selling spare emission credits. Under emission constraints, the manufacturer needs to schedule its production under, at, or over the assigned emission cap for the profit optimality.

Demand uncertainty always causes profit haemorrhage. Failure to meet the vital demand would either lead to product shortage or redundant emission cost. Solving the demand uncertainty is important for the emission and production strategy.

Normally, the customers are inclined to green-labelled products with the same quality. Thus, the end demand experiences a corresponding growth with emission reduction. For instance, H&M has adopted green technologies to minimize carbon emission in the production process and launched these green-labelled products to attract green customers (Dong et al., 2016). This demand increase will inspire the manufacturer to invest more in the green upgrade that raises the product cost. How to allot the emission cost and the investment cost is key to operation success. This research also solves this problem for optimality.

This paper contributes to solving the emission ordering problem with green awareness under the emission-constrained market by newsvendor models. Due to its complexity of calculation, the Lagrange multipliers are employed to simplify the calculation process where the Karush-Kuhn-Tucker (KKT) conditions are used to achieve the optimal results. It gives guidance for the emission-dependent firms to gain optimality facing the extra emission burdens.

2 LITERATURE STUDY

This section briefly reviews some previous research works related to the decision analysis with green awareness under the emission trading scheme (ETS).

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2.1 Emission Trading Scheme (ETS)

The Emission Trading Scheme (ETS), the first and the largest emission-restricted policy, gains its popularity since the 1970s (Burton and Sanjour, 1970). Many researchers and policy-makers have theoretically and practically proven its efficiency to achieve emission reduction targets.

Ellerman and Buchner (2007) discussed the origins, allocation, and the early results of the European Union emission trading scheme (EU ETS), and concluded that the EU ETS has succeeded in imposing a price on CO2 emission. Ellerman (2010) analysed the problem of the trial run of the EU ETS which are being addressed seriously. Kirat and Ahamada (2011) pointed out that the main objectives of the EU ETS are to encourage the emitters to reduce their carbon emission and invest in clean technologies. Borghesi (2011) discussed the merits and limits of the EU ETS and argued that more credible targets for carbon emission reduction are required for the success of ETS. Martin et al. (2015) said that the EU ETS must provide incentives not only for emission abatement in the short run but also for innovation in clean technologies to be dynamically efficient.

In practice, the EU ETS regulates around 45% of the total EU emission, and is projected to reduce 43% carbon emission by 2030 compared to 2005 (European Commission, 2017). This means the manufacturing industry, as a big emission emitter, burdens great emission pressure in the emission-limited environment.

Therefore, it is important for the manufacturers to plan their emission and green investment strategies to thrive in this stringent emission market.

2.2 Green Awareness

Green awareness is the behaviour that a customer is inclined to environmental-friendly products or services (Hussain et al., 2014).

Sheu and Li (2013) concluded that customers' green awareness will shape a new strategy against carbon emission, as the customer's inclination to green-labelled products influences them to accept a higher price. Li et al. (2016) opined that the increasing green awareness will make the competition fiercer, and thus it plays an important role in achieving emission reduction targets and in some way increasing the demand uncertainty.

Schlegelmilch et al. (1996) showed that customer's green awareness will impact on their purchasing behaviour, and this may affect the demand patterns. Yadav and Pathak (2016) further proved that young customers prefer to purchase green products or services. Maniatis (2016) pointed out that the US customers spend $25 Billion per year on green-labelled products. Green awareness is, therefore, essential for the manufacturer to shape its production strategy.

Wang et al. (2016) formulated the demand function is positively affected by the emission reduction level. Xu et al. (2017) defined their demand is low-carbon preference and built an additive demand function. Based on their work, this research assumes the demand is homogeneous in its preference for the product green level and follows the normal distribution.

3 MODEL FORMULATION

This section mathematically explores the decision behaviours and profit performance of a manufacturer with demand uncertainty under the ETS system by Newsvendor models. The Lagrange Multipliers and KKT conditions are used to solve this problem.

3.1 Notations and Assumptions

The following notations are employed throughout this research.

Table 1: Notations for demand function.

Demand Function	Description
$D(i,\varepsilon)$	The stochastic green-driven demand function for the single product, which is continuous and differentiable. $D(i,\varepsilon)=y(i)+\varepsilon$.
$y(i)$	The increasing and deterministic demand function for emission abatement level. $y(i)=a+bi$.
i	The emission abatement level.
a	The market scale for the single product. $a>0$.
b	The green sensitivity to the demand. $b>0$.
ε	The random variable for the demand uncertainty. $\varepsilon\in[A,B]$, $E(\varepsilon)=\mu$. $A>-a$.
$f(\cdot)$	The probability density function for ε.
$F(\cdot)$	The non-negative, invertible distribution function for ε.

Table 2: Notations for parameters.

Parameters	Description
p	The unitary selling price of the product.
e	The emission level of the product
K	The emission cap
c	The unitary cost of the product, including production, inventory, and managerial cost, etc.
w_b	Emission credit price
s	The resold price of the spare emission credits
g	The unitary goodwill cost for the unsatisfied demand.
H	The cost factor of green investment
λ	The Lagrange Multipliers
η^2	The slack variables
x^+	The larger value comparing zero with x , $x^+ = \max(0,x)$

Table 3: Notations for decision variables.

Decision Variables	Description
q	The total emission quantity needed
i	Emission abatement level
q_s	The spare emission credit quantity
Q	The production quantity
r	The stocking factor when $q \ge 0$
z	The stocking factor when $q \le 0$

Some specific assumptions are made as follows:

Assumption 1: The manufacturer has no capacity limit except emission quotas.

Assumption 2: The demand is positive, and the profit is non-negative.

Assumption 3: The additive demand function is used to build the green-driven demand with uncertainty.

$D(i,\varepsilon) = y(i) + \varepsilon$, $y(i) = a + bi \ \ (a > 0, b > 0)$

$\varepsilon \in [A, B]$, $A > -a$, $E(\varepsilon) = \mu$.

3.2 Model Building

3.2.1 Model Description

This scenario assumes the manufacturer can purchase emission credits provided by emission permit suppliers and invest in green upgrade to reduce the unit carbon emission level. The batch production is scheduled upon the emission credits received.

The firm decides its emission abatement level i^n and orders q^n emission credits for producing $\left(q^n + K\right)/\left(e - i^n\right)$ product units sold at the unitary selling price p^n . The key to assuring production is to hold sufficient emission credits, and the spare credits can be disposed of at the resold price s . The profit model is given as:

$$\begin{cases} \Pi\left(q^n, i^n\right) = \left(p - c\right) \cdot \min\left[D, \dfrac{q^n + K}{e - i^n}\right] \\ + s \cdot \left(e - i^n\right) \cdot \left[\dfrac{q^n + K}{e - i^n} - D\right]^+ - g \cdot \left[D - \dfrac{q^n + K}{e - i^n}\right]^+ \\ - w_b \cdot q^n - H \cdot i^{n2} \\ s.t.\ \ q^n \ge 0,\ 0 \le i < e \end{cases} \quad (1)$$

This model defines the stocking factor as $r^n = \dfrac{q^n + K}{\left(e - i^n\right)} - y\left(i^n\right)$, and it is the riskless leftover which neglects the impact of demand uncertainty. Compared with the demand uncertainty variable ε , credit leftover occurs when $r^n > \varepsilon$, and shortage when $r^n < \varepsilon$.

By inserting this stocking factor r^n and the demand function $D\left(i^n, \varepsilon\right) = y\left(i^n\right) + \varepsilon$, the profit model is built as:

$$\begin{aligned} &\Pi\left(r^n, i^n\right) = \\ &\left(p - c\right) \cdot \min\left[y\left(i^n\right) + \varepsilon, y\left(i^n\right) + r^n\right] - H \cdot i^{n2} \\ &+ s \cdot \left(e - i^n\right) \cdot \left[r^n - \varepsilon\right]^+ + w_b \cdot K - g \cdot \left[\varepsilon - r^n\right]^+ \\ &- w_b \cdot \left(e - i^n\right) \cdot \left[\left(y\left(i^n\right) + r^n\right)\right] \end{aligned} \quad (2)$$

To simplify the calculation, we define $\Lambda\left(r^n\right) = \int_A^{r^n} \left(r^n - x\right) f\left(x\right) dx$ for the expected product leftover and $\Gamma\left(r^n\right) = \int_{r^n}^{B} \left(x - r^n\right) f\left(x\right) dx$ for the expected product shortage. Then we have the expected profit, denoted $E\left[\prod\left(r^n,i^n\right)\right]$, as follows:

$$\begin{aligned}
&E\left[\prod\left(r^n,i^n\right)\right]= \\
&\left[p-c-w_b\cdot\left(e-i^n\right)\right]\cdot\left[y\left(i^n\right)+\mu\right]+w_b\cdot K \\
&-\left(w_b-s\right)\cdot\left(e-i^n\right)\cdot\Lambda\left(r^n\right) \\
&-\left[p-c+g-w_b\cdot\left(e-i^n\right)\right]\cdot\Gamma\left(r^n\right)-H\cdot i^{n2}
\end{aligned} \tag{3}$$

For simplification, it can be written as:

$$E\left[\prod\left(r^n,i^n\right)\right]=\psi\left(i^n\right)-\chi\left(r^n,i^n\right) \tag{4}$$

Where

$$\begin{aligned}
&\psi\left(i^n\right)=\left[p-c-w_b\cdot\left(e-i^n\right)\right]\cdot\left[y\left(i^n\right)+\mu\right] \\
&+w_b\cdot K-H\cdot i^{n2} \\
&\chi\left(r^n,i^n\right)=\ \left(w_b-s\right)\cdot\left(e-i^n\right)\cdot\Lambda\left(r^n\right) \\
&+\left[p-c+g-w_b\cdot\left(e-i^n\right)\right]\cdot\Gamma\left(r^n\right)
\end{aligned} \tag{5}$$

Then we can have the expect profit function under the emission restrictions, as follows:

$$\begin{cases}
E\left[\prod\left(r^n,,i^n\right)\right]=\psi\left(i^n\right)-\chi\left(r^n,i^n\right) \\
s.t.\quad K-\left(e-i^n\right)\cdot\left(y\left(i^n\right)+r^n\right)\le 0
\end{cases} \tag{6}$$

3.2.2 Problem Solving

The Lagrange Multipliers are explored to solve this problem, as it is a widely used strategy for finding the local maxima and minima of a function subject to equality constraints.

To solve this problem, the Lagrange Multipliers are explored and a slack variable η_1^2 is adopted. Then the problem can be re-written as:

$$\begin{cases}
L\left(r^n,i^n,\eta_1,\lambda_1\right)=-\psi\left(i^n\right)+\chi\left(r^n,i^n\right) \\
+\lambda_1\cdot\left[K-\left(e-i^n\right)\cdot\left(y\left(i^n\right)+r^n\right)+\eta_1^2\right] \\
s.t.\ \ \lambda_1\ge 0
\end{cases} \tag{7}$$

The Karush-Kuhn-Tucker (KKT) conditions are the first-order necessary conditions for a solution in a non-linear programming to get optimality, given some regularity conditions are satisfied. And this problem with the Lagrange Multipliers can be solved by the KKT conditions, as follows:

$$\begin{cases}
\dfrac{\partial L}{\partial i^n}=2\left(H-w_b\cdot b\right)\cdot i^n-w_b\cdot\left(a-b\cdot e+\mu\right) \\
\quad -b\cdot\left(p-c\right)+w_b\cdot\Gamma-\left(w_b-s\right)\cdot\Lambda \\
\quad +\lambda_1\cdot\left(a+2b\cdot i^n-b\cdot e+r^n\right)=0 \\
\dfrac{\partial L}{\partial r^n}=-\left[p-c+g-w_b\cdot\left(e-i^n\right)\right] \\
\quad +\left[p-c+g-s\cdot\left(e-i^n\right)\right]\cdot F\left(r^n\right) \\
\quad -\lambda_1\cdot\left(e-i^n\right)=0 \\
\dfrac{\partial L}{\partial \eta_1}=2\eta_1\cdot\lambda_1=0 \\
\dfrac{\partial L}{\partial \lambda_1}=K-\left(e-i^n\right)\cdot\left(y\left(i^n\right)+r^n\right)+\eta_1^2=0
\end{cases} \tag{8}$$

Then we can have the optimal results by $\lambda_1=0$ and $\eta_1=0$.

(1) When $\lambda_1=0$, no spare emission credits exist. From $\frac{\partial L}{\partial i^n}=0$, we have $i^n=\varphi\left(r^n\right)$. Then inserting this expression into $\frac{\partial L}{\partial r^n}=0$, we can have the optimal r^{n*} by solving $\frac{\left[p-c+g-s\cdot\left(e-\varphi\left(r^n\right)\right)\right]}{e-\varphi\left(r^n\right)}=w_b-s$.

Results:

We have the optimal i^{n*} as $i^{n*}=\varphi\left(r^{n*}\right)$; and the optimal total emission quantity q^{n*} as $q^{n*}=\eta_3^2=\left(e-i^{n*}\right)\cdot y\left(i^{n*}\right)+r^{n*}-K$.

***Lemma 1*:** When $\lambda_1=0$, the optimal stocking factor r^{n*} is uniquely determined by the equation $\frac{\left[p-c+g-s\cdot\left(e-\varphi\left(r^n\right)\right)\right]}{e-\varphi\left(r^n\right)}=w_b-s$. Thus, the firm invests in $i^{n*}=\varphi\left(r^{n*}\right)$ emission abatement level and requires $q^{n*}=\eta_1^2=\left(e-i^{n*}\right)\cdot y\left(i^{n*}\right)+r^{n*}-K$ emission credits from the emission credits supplier.

(2) When $\eta_1=0$, no emission credits are required.

This situation means the firm just produces the emission-capped quantity. Then another model is built where the firm only produces under emission cap, and benefits from selling its spare emission. The new expected profit function is:

$$\begin{cases} \Pi(Q,i) = (p-c)\cdot \min[D,Q] - H\cdot i^2 \\ \qquad + s\cdot[K-(e-i)\cdot Q]^+ - g\cdot[D-Q]^+ \\ s.t. \quad (e-i)\cdot Q \le K \end{cases} \tag{9}$$

The stocking factor used in this model is $z = Q - y(i)$. By inserting this stocking factor z and the demand function $D(i,\varepsilon) = y(i) + \varepsilon$, and defining $\Phi(z) = \int_A^z (z-x) f(x) dx$ for the leftovers of the products, and $\Upsilon(z) = \int_z^B (x-z) f(x) dx$ for the shortage of the products, the profit model is built like:

$$\begin{aligned} E[\Pi(z,i)] = & [p-c-s\cdot(e-i)]\cdot[y(p)+\mu] \\ & + s\cdot K - H\cdot i^2 - s\cdot(e-i)\cdot\Phi(z) \\ & -[p-c+g-s\cdot(e-i)]\cdot\Upsilon(z) \end{aligned} \tag{10}$$

For simplification, it can be written as:

$$E[\Pi(z,i)] = \psi(i) - \chi(z,i) \tag{11}$$

Where

$$\begin{aligned} \psi(i) = & [p-c-s\cdot(e-i)]\cdot[y(p)+\mu] \\ & + s\cdot K - H\cdot i^2 \\ \chi(z,i) = & [p-c+g-s\cdot(e-i)]\cdot\Upsilon(z) \\ & + s\cdot(e-i)\cdot\Phi(z) \end{aligned} \tag{12}$$

Then we can have the expect profit function under the emission restrictions, as follows:

$$\begin{cases} E[\Pi(z,i)] = \psi(i) - \chi(z,i) \\ s.t. \quad (e-i)\cdot(y(i)+z) - K \le 0 \end{cases} \tag{13}$$

To solve this problem, the Lagrange Multipliers are explored and a slack variable η_2^2 is adopted. Then the problem can be re-written as:

$$\begin{cases} L(z,i,\eta_2,\lambda_2) = -\psi(p,i) + \chi(z,p,i) \\ +\lambda_2\cdot[(e-i)\cdot(y(i)+z) - K + \eta_2^2] \\ s.t. \ \lambda_2 \ge 0 \end{cases} \tag{14}$$

This problem with the Lagrange Multipliers can be solved by the KKT conditions, as follows:

$$\begin{cases} \dfrac{\partial L}{\partial i} = 2(H-s\cdot b)\cdot i - (p-c)\cdot b \\ \qquad + s\cdot[\Upsilon(z) - \Phi(z) - a + b\cdot e - \mu] \\ \qquad - \lambda_2\cdot(2b\cdot i + a + z - b\cdot e) = 0 \\ \dfrac{\partial L}{\partial z} = -(p-c+g)\cdot\overline{F}(z) \\ \qquad + s\cdot(e-i) + \lambda_2\cdot(e-i) = 0 \\ \dfrac{\partial L}{\partial \eta_2} = 2\lambda_2\cdot\eta_2 = 0 \\ \dfrac{\partial L}{\partial \lambda_2} = (e-i)\cdot(a+b\cdot i+z) - K + \eta_2^2 = 0 \end{cases} \tag{15}$$

Then we can have the optimal results by $\lambda_2 = 0$ and $\eta_2 = 0$.

(1) When $\lambda_2 = 0$, spare emission credits exist.

From $\dfrac{\partial L}{\partial i} = 0$, we have the expression $i = \varsigma(z)$. Inserting the expression $i = \varsigma(z)$ into $\dfrac{\partial L}{\partial z} = 0$, we have the optima z^* by solving the following expression $(p-c+g)\cdot\overline{F}(z) = s\cdot(e-\varsigma(z))$.

Results:

We have the optimal i^{S*} as $i^{S*} = \varsigma(z^*)$; the optimal total emission quantity Q^{S*} as $Q^{S*} = a + b\cdot i^{S*} + z^*$; and the spare emission q_s^{S*} as $q_s^{S*} = \eta_2^2 = K - (e - i^{S*})\cdot(a + b\cdot i^{S*} + z^*)$.

***Lemma 2*:** When $\lambda_2 = 0$, the optimal stocking factor z^* is uniquely determined by the equation $(p-c+g)\cdot\overline{F}(z) = s\cdot(e-\varsigma(z))$. Thus, the firm invests in $i^{S*} = \varsigma(z^*)$ emission abatement level and resells the spare emission credits $q_s^{S*} = \eta_2^2 = K - (e - i^{S*})\cdot(a + b\cdot i^{S*} + z^*)$ to the emission market and produces $Q^{S*} = a + b\cdot i^{S*} + z^*$ products.

(2) When $\eta_2 = 0$, no spare or extra emission credits exist.

From $\dfrac{\partial L}{\partial \eta_2} = 0$, we have $i = \upsilon(z)$. By inserting $i = \upsilon(z)$ into $\dfrac{\partial L}{\partial i} = 0$ and $\dfrac{\partial L}{\partial z} = 0$, we have the optimal z^* by solving the expression $\Theta(z)$ as:

$$\frac{2(H-s\cdot b)\cdot\upsilon(z)+s\cdot\left[\Upsilon(z)-\Phi(z)-a+b\cdot e-\mu\right]-(p-c)\cdot b}{2b\cdot\upsilon(z)+a+z-b\cdot e}=\frac{(p-c+g)\cdot\overline{F}(z)-s\cdot(e-\upsilon(z))}{(e-\upsilon(z))}$$

Results:

We have the optimal emission abatement level $i^{K*}=\upsilon(z^*)$ by solving the expression $\Theta(z)$; and the optimal total emission quantity Q^{K*} as $Q^{K*}=\dfrac{K}{e-i^{K*}}$.

Lemma 3: When $\eta_2=0$, the firm invests in $i^{K*}=\upsilon(z^*)$ emission abatement level and produces $Q^{K*}=\dfrac{K}{e-i^{K*}}$ products by solving $\Theta(z)$.

Lemma 4: The firm can achieve its optimality when $\lambda_1=0,\lambda_2=0$ or $\eta_2=0$.

4 NUMERICAL STUDY

The Chinese fertilizer industry is an intensive energy user and carbon emitter. It is, therefore, crucial for this industry to reduce emission.

The following data in Table 4 are collected from the Chinese fertilizer industry to conduct the numerical study. Data are from a report of a phosphate fertilizer company.

Table 4: Data for numerical study.

e	K	c	s	g	w_b	H	p
0.9	0.8	200	5	10	10	50000	300
ton/ ton	100 ton	USD/ ton	USD/ ton	USD/ ton	USD/ ton	USD	USD

4.1 Results Comparison

Based on the above dataset, we have the numerical results in Table 5. We can see that the best strategy is ordering 160.87 (100 ton) emission credits and reducing 0.0772 emission abatement level to attract more demand. If the firm only produces the emission-capped quantity, it needs to invest more in green upgrade to increase its production capacity. However, its end revenue is nearly halved.

Table 5: Results comparison.

	Unit	$\lambda_1=0$	$\lambda_2=0$	$\eta_2=0$
Emission abatement level	--	0.0772	0.0637	0.2385
Emission credits quantity	100ton	160.87	0	0
Spare credits quantity	100ton	0	-165.01	0
Production quantity	100ton	260.87	316.89	151.17
Resulted profit	1000USD	2132.46	2177.09	1262.19
Final profit	1000USD	2132.46	0	1262.19
Best strategy	--	2132.46	--	--

4.2 Sensitivity to Demand Uncertainty

Figure 1 shows how the performance and decision behaviours vary with increasingly fierce demand uncertainty. Here, we use the coefficient of variation (CV) to measure the demand risk. For the case selection, 1 refers to ordering emission credits; 2 refers to producing under emission cap; and 3 refers to just producing the emission-capped quantity.

From 1(a) we can see the profit decreases with increasing demand uncertainty. Ordering emission credits makes the manufacturer more profitable as shown in 1(b). In 1(c), we know that more investment cost is needed to hedge the demand risk, as the firm needs more inventory buffers to satisfy the unplanned orders. 1(d) shows that the firm tends to hold more emission credits when the demand uncertainty is higher.

Managerial Insight 1: More green investment and more emission credits are needed to hedge the demand uncertainty, which lowers the firm's profitability.

Managerial Insight 2: The firm tends to order extra emission credits to enlarge its production capacity facing rational demand uncertainty.

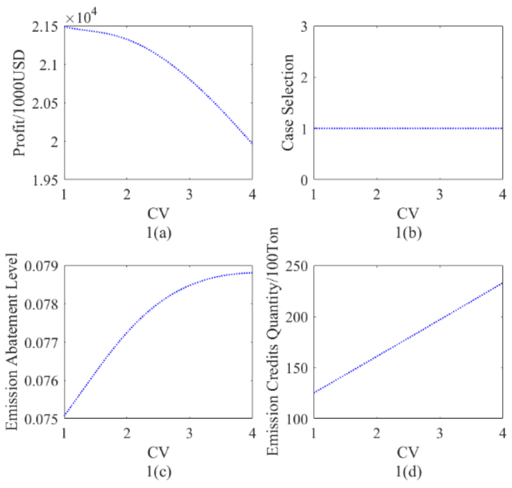

Figure 1: Sensitivity to demand uncertainty.

4.3 Sensitivity to Emission-related Factors

This section discusses the changes of the manufacturer's performance and decision behaviours with emission-related factors, namely green sensitivity to demand, emission cap, and emission credit price.

4.3.1 Green Sensitivity to Demand

From 2(a) and 2(c), we know that the firm invests more in green upgrade and earns more profit when the customers pay more attention to the green-labelled products. Correspondingly, less emission credits are required as the production activity enjoys a smaller emission level. As shown in 2(b), the best strategy is to order extra emission credits in almost all the green sensitivity to demand.

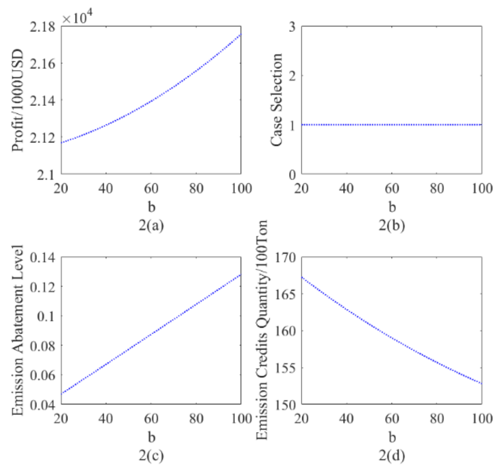

Figure 2: Sensitivity to green-demand factor.

4.3.2 Emission Cap

As shown in 3(a), the firm thrives better with loose emission constraints. From 3(b), we can see the best strategy is to order extra emission credits in almost all the emission markets. 3(c) shows that the changes of emission cap do not affect the emission abatement level, that means, the investment strategy acts beyond the influence of tightness of emission market. Obviously, less emission credits are required with loose emission restrictions, as shown in 3(d).

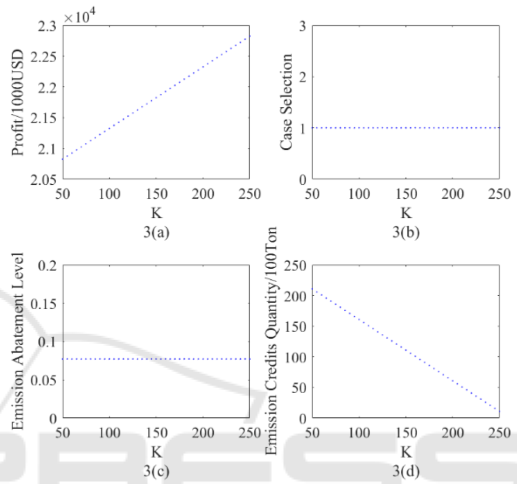

Figure 3: Sensitivity to emission cap.

4.3.3 Emission Credit Price

From 4(a) and 4(d), we can see that the higher emission credit price reduces both the profitability and the emission credit quantity, since purchasing one-unit emission charges more money. 4(b) tells that the firm performs better by ordering extra emission credits. The firm tends to invest more in green-upgrade with higher emission cost, as shown in 4(c).

***Managerial Insight 3*:** The firm tends to implement more green investment with more green awareness and higher emission cost.

***Managerial Insight 4*:** The firm better thrives in the loose emission market, where green awareness rises.

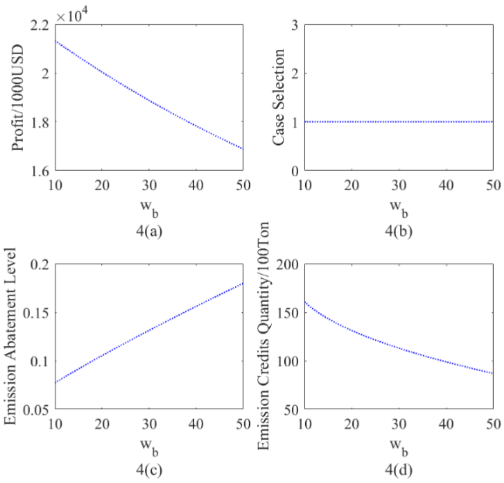

Figure 4: Sensitivity to emission credit price.

4.4 Sensitivity to Price Factors

This section discusses how the performance and decision behaviours vary with price factors, namely, cost factor of green investment and selling price of the product.

4.4.1 Cost Factor of Green Investment

Obviously, the higher investment cost lowers the profitability, as shown in figure 5(a). From 5(b) the firm better operates with more emission out of purchasing. In 5(c) and 5(d), we can see the emission abatement level decreases and emission credit quantity increases with higher investment cost factor.

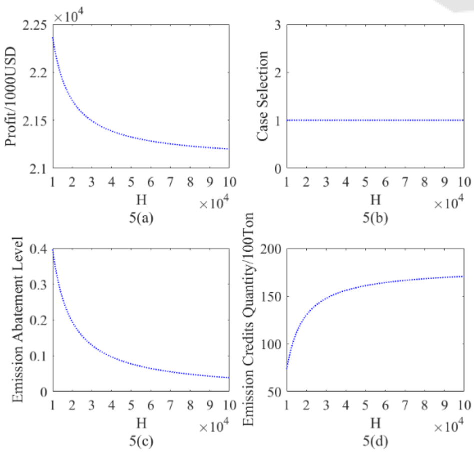

Figure 5: Sensitivity to emission credit price.

4.4.2 Selling Price of the Product

From 6(a), the firm earns more by charging a higher selling price of the product. Similarly, buying extra emission credits is a better strategy in 6(b). With higher selling price, the firm can make more effort in green investment, as shown in 6(c). In 6(d), we can see the trend of emission credit quantity is intricate, increasing and then decreasing. The reason is that the firm prefers to produce more when the selling price is relatively high. However, from 6(c) and 6(d), we know that green investment lowers the emission level, and thus it will not need to purchase more emission to ensure production, when the selling price is relatively high.

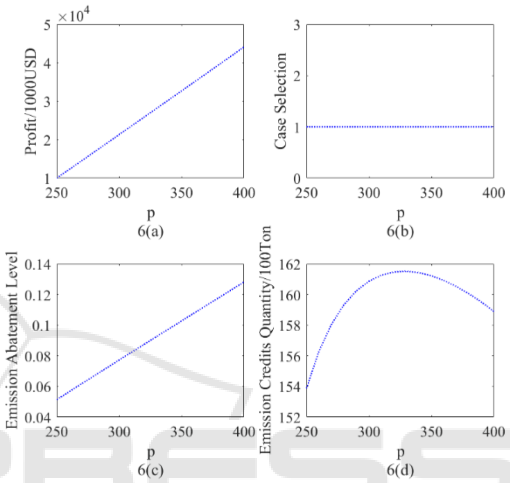

Figure 6: Sensitivity to emission credit price.

***Managerial Insight 5*:** The firm tends to implement more green investment with lower investment cost factor and higher selling price.
***Managerial Insight 6*:** The best strategy is to purchase extra emission in almost all the situations.

5 CONCLUSIONS

This research studies the emission strategy under an emission-limited market, where the customers are inclined to green-labelled products. Newsvendor models are used to solve this problem. Its novelty lies in the use of the Lagrange Multipliers and KKT conditions to achieve the optimality subject to emission constraints.

Three emission ordering strategies are discussed and analysed, namely ordering extra emission credits, producing under the emission cap, and just producing emission-capped quantity. Except for the emission quantity, emission abatement level is considered to attract more customer demand.

From the analytical results, we can achieve the optimal emission strategy by comparing the profitability in these three cases. In almost all the situations, the firm better thrives by ordering extra emission credits. More green investments are required when the demand risk, green awareness, emission credit price, and selling price of the product increase. The firm needs to hold more emission to hedge higher demand uncertainty.

These findings call for the manufacturer to make better decisions for achieving both the optimality and the emission reduction.

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