

Low-carbon Supply Chain Coordination through Dual Contracts Considering Pareto-efficiency

Shuyi Wang¹, S.H. Choi², Jianhua Xiao³, George Q. Huang*

Abstract: Considering the growing green awareness and increasingly stringent emission regulations, heavy-emitting supply chains are required to re-schedule their operations for environmental responsibility. Although coordination helps the supply chains overcome the decentralized disadvantages to achieve desirable profits, literature considering option contracts under emission constraints, especially combining warehousing contracts, remains scarce. This paper fills this research gap with the novelty in the dual-contract-coordinated decision analysis for achieving profit maximum and emission reduction targets considering customers' green awareness through option and warehousing contracts, based on the originality of using the Lagrange-Stackelberg optimization method, which overcomes the difficulty in expressing the first-mover's decisions and simplifies the problem-solving process. Analytical and numerical results show that Pareto-efficient coordination can be fully achieved by the option contract if the warehousing contract ensures the same inventory costs before and after coordination. Otherwise, partial coordination also raises insiders' profitability only through the option contract. Purchasing extra emissions with green investment is the best in most cases. The contract-maker should deliberate its contract settings including the option and wholesale prices, as well as warehousing, to develop Pareto-efficient coordination. Sustainability comes at a cost, but coordination raises profitability and emission mitigation in a well-built ETS market.

Keywords: SDG 17: Partnerships for the Goals; Low-carbon Supply Chain; Pareto-efficient Coordination; Dual Contracts

I. INTRODUCTION

* Corresponding Author

E-mail: gq.huang@polyu.edu.hk

Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University

¹ E-mail: wang0214@connect.hku.hk

Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong

² E-mail: shchoi@hku.hk

Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong

³ E-mail: jhxiao@nankai.edu.cn

The Research center of Logistics, Nankai University, Tianjin, China

To curb the drastic rise in atmospheric temperature, the 43rd Session of the Intergovernmental Panel on Climate Change (IPCC) has set a target to cut emissions by 40-70% in 2050 compared to 2010 (Intergovernmental Panel on Climate Change, 2014). Due to the inevitable trend and worldwide consensus on emission reduction, many changes have occurred in the way the supply chains traditionally function. A BearingPoint survey in 2011 showed that most (70%) companies in Europe advocate a low-carbon supply chain and 56% of companies think it brings measurable profits. Low-carbon processing becomes a critical supply chain issue that entails the efforts of all the insiders. These insiders become more environmentally responsible when more customers understand the fragility of ecosystems and the importance of environmental sustainability. A European survey found that 83% of European purchasers hold green awareness, and 75% of customers would purchase greener products at a higher price (Brécard, 2013). This green awareness subsequently encourages companies to be involved in low-carbon operations (Moon et al., 2002). For instance, it is reported that Apple Inc. has been cooperating with its manufacturing suppliers and permits to be carbon neutral by 2030 via clean energy (Apple. Inc., 2020). LafargeHolcim cement has performed carbon-efficient and has achieved 27% emission-cutting since 1990 through upgrading their plants and purchasing renewable energy. CF Industries Holdings Inc. has invested in technologies and equipment to drive low-carbon improvement in fertilizer production. Hewlett-Packard, Walmart, Tesco, and Patagonia have required their suppliers to meet the emission requirements (Luo et al., 2016). These companies have green-labelled their products for the customers' consideration of emission index beyond price and quality. Albeit green investments and product charges more on each insider, the operators are likely to upgrade their production or purchase greener raw materials.

However, it is far from enough to reduce carbon emissions only by voluntary means. Low-carbon processing is triggered by the growing emission reduction pressure from regulatory bodies. Mandatory emission reduction targets are imposed under the Emission Trading Scheme (ETS), which has become an international emission scheme that covers much of the world (Wang & Choi, 2020a). Aggregate emission limits are capped, and emission credits are allowed to be traded within the emission market. The ETS is a bi-directional incentive-constraint mechanism between supply chain insiders and regulatory bodies. Under this mechanism, shortage of emission credits incurs costs but leftover brings about profits, making supply chain decisions more complicated. The insiders need to weigh up the earnings from selling spare emissions and the higher sales from buying extra emissions.

Under an emission-capped ETS market, the supply chain members have to solve more complicated decision problems considering the mentioned incentives and regulations of emission reduction. This research targets to explore the best low-carbon operations of a risk-bearing supply chain through dual-contract-based coordination under the ETS, which attempts to achieve the synergistic development of the environment and economy. Demand uncertainty compounds the difficulties of supply chain operations. Failures to predict demands lead to profit haemorrhage (Wang & Choi, 2019). For

instance, customers in Canada initially welcomed the expansion of Target's stores, but all 133 Target stores were closed down in 2015 due to its misprediction about Canadians' enthusiasm in the retail industry (Begen et al., 2016). Fortunately, supply chain coordination can alleviate this problem by quickly responding to its downstream customers. Normally, decentralized decision-making results in a profit discrepancy compared with the integrated maximum. Coordination helps the supply chain overcome the decentralized disadvantages for achieving the desirable profits. Moreover, scholars have proven its ability to improve the sustainable performance of the supply chain (Seuring & Müller, 2008).

Properly designed contracts possess desirable mechanistic features to facilitate supply chain coordination. Only when Pareto improvement, under which no one would be hurt but are all likely to gain, is satisfied will contracts be reached (Wang & Choi, 2020c). Accordingly, dual-contract coordination considering Pareto efficiency through option and warehousing contracts will be investigated to improve the profitability and sustainability of both the whole supply chain and all its insiders. While the warehousing contract attracts considerable academic discussions (Chen et al., 2001), the option contract is widely used in industries. It can effectively secure sufficient supplies to meet uncertain demands and a negotiated price ensures that the downstream insiders can afford the additional demand. 35% of Hewlett-Packard's (HP) procurement value was reportedly from option contracts (Chen et al., 2014). The Intel Corporation achieved a cost-saving of tens of millions of dollars through option contracts (Peng et al., 2012). The famous e-commerce retailer in China, Suning Commerce Group, also used options to avoid excess stock (Cai et al., 2016). However, few studies have considered option contracts in coordinated decision-making (Hong & Guo, 2019), especially combining warehousing contracts under emission constraints, due to the calculation difficulty. This paper fills this research gap through dual-contract coordination. It characterises the Pareto-efficient contracts through pricing strategies, under which no one would be hurt but all are likely to gain from coordination. Moreover, the effective system settings of the ETS are discovered for its synergistic operation on economic development and emission control.

In particular, the present work tries to address the following research questions: (1) How the emission constraints, green awareness, and demand uncertainty affect the decisions of the supply chain insiders and their final profits? (2) Can the dual contracts (the option contract and the warehousing contract) coordinate the supply chain and promote profits and emission mitigation significantly? and (3) Will the Pareto improvement be achieved through the dual contracts?

A two-stage supply chain, including one retailer and one manufacturer, is discussed in the make-to-order (MTO) pattern. According to the works by Wang and Choi (2020c), the manufacturer has enough bargaining power to be the leader in a Stackelberg game. Thus, the call option contract is provided by the manufacturer concerning option and exercising prices, meanwhile, a warehousing contract is used to minimize the inventory costs. This coordination study combines the pricing and

production problems with emission decisions. Game-theoretic models are proposed to solve this M-leader Stackelberg coordination problem, in which the manufacturer moves first and then the retailer moves sequentially. Usually, it is hard to analytically address the coordination problem with uncertain demand, and the contracts and emission requirements make the Stackelberg model more complicated.

This paper first considers the Lagrange-Stackelberg optimization method, combining the retailer's and manufacturer's decision-making process, to make solving the problem possible. The ordinary problem-solving method needs to achieve the expression of the retailer's decision variables, which are subsequently inserted into the manufacturer's profit models for the final results. Only if the expressions of the retailer's decision variables can be written, the following manufacturer's process can continue with a possible solution. However, the retailer's decisions are often not expressible, limiting the feasibility of the ordinary method. Our method extracts the essence of the Lagrangian method. It regards the equality conditions from the retailer's process as the Lagrange constraints for the following manufacturer's decision-making problem. This method overcomes the difficulty in expressing the first-mover's decisions and simplifies the problem-solving process. All in all, this method can analytically solve the complicated coordination problem.

The objective of this research is to investigate the optimal low-carbon decision-making of a risk-bearing and green-inclined supply chain through coordination by both option and warehousing contracts under the ETS, with the aim of synergistic benefits in profitability and sustainability. The contributions of this research can be summarised in the following aspects:

- (1) A dual-contract coordination problem is discussed with option and warehousing contracts, which are rarely used to help emission-dependent firms fulfil their emission requirement with profit increase.
- (2) Pareto-efficient contracts for win-win conditions and effective ETS system settings for its synergistic operation on economic and environmental development are developed.
- (3) A novel Lagrange-Stackelberg optimization method is proposed to analytically solve game-theoretic models with complications in the solution process.
- (4) Managerial insights are derived for the supply chain and suggestions for the policy-makers to develop the economy under a sustainable market.

The novelty of this research lies in the dual-contract coordination which addresses the uncertain demand and emission problem under the ETS. Literature works considering option contracts to coordinate the supply chain under emission constraints remain scarce, and our research enriches this academic area by combining warehousing contracts. Moreover, the M-leader Stackelberg game is analytically solved by using the Lagrange-Stackelberg method, which overcomes the difficulties in

writing the expressions. Synergistic benefits achievable through coordination depend on prices, and this requires the contract designers and policy-makers to be rational in their pricing strategy.

II. LITERATURE STUDY

This literature study briefly reviews the previous literature to identify the existing research gaps and set out the theoretical bases.

2.1 The Emission Trading Scheme and Green Awareness

The ETS has gained popularity in emission reduction since the 1970s (Burton & Sanjour, 1970). Scholars and regulatory bodies hold positive attitudes towards its international establishment, according to ETS research conducted in different countries and industries (Wang & Choi, 2020a). The major ETS markets, including the European Union, the UK, the US, Canada, Australia, New Zealand, Japan, and China, have all built the ETS markets with their own emission targets, and the corresponding results show that the ETS is effective in reducing emission under the implementation period. Villoria-Sáez et al. (2016) discussed the effectiveness of the ETS in six regions among these markets, excluding the UK and China. They reported encouraging results that underscore the need to further implement the ETS. Smith and Swierzbinski (2007) advocated the UK ETS due to its acceptable economic and environmental results. The UK experienced a 29.8% cut in emissions resulting from its ETS between 1990 and 2013 (Martin et al., 2016). China's seven pilots have achieved practical results and its official ETS market was launched in December 2017. China's emissions have significantly dropped in the pilot period (Lin & Jia, 2017, 2019), which can be attributed to the ETS. All these practical achievements and research works above prove that the ETS needs to be continually implemented and further studied.

Moreover, Martin et al. (2016) argued that the dynamic efficiency of the EU ETS relies on its incentives for not only emission abatement but the innovation in green technologies. Meanwhile, green awareness concerning a low-carbon lifestyle encourages supply chain insiders to put efforts into green upgrades in their production and operation. Du et al. (2015) investigated the impact of customer's green awareness in a carbon-concerned supply chain and concluded that both profitability and sustainability increase in customer's preference to low-carbon products. Yu et al. (2022) pointed out that green awareness has been prompting more firms to set abatement targets. Sana (2022b) provided evidence that firms have been adopting green technologies to procure green products since people become more conscious about emission abatement for environmental protection. Although green technology for emission reduction costs more, green customers are willing to compensate for it at a higher price. The need to purchase less-emission products rises with the increasing number of green customers (Chitra, 2007; Moon et al., 2002). Yakita (2009) provided evidence that the sales of hybrid cars increased by 19.25% with 1.5 times the ordinary price. Major companies, therefore, are likely to invest in green technology for sustainability. For instance, The Mosaic Company has put

efforts into green technology to achieve a 25% emission reduction, while P&G has promised to reduce its emissions by 20% via upgrading its facilities (Du et al., 2016). JingDong established China's first "zero carbon" logistics park in 2021, under which some emissions are neutralized by the roof-distributed photovoltaic power generation systems and energy storage systems, and the remains are offset by purchasing emission credits (Huang et al., 2023). Sana (2020) studied the pricing strategy of green products in comparison to non-green products under emission constraints and the optimal investment in green technology to reduce emissions. Green investment has become a critical approach to obtaining the emission certificate in line with greater public appeal. Supply chain coordination for sustainability has accelerated the progress in implementing green technology (Chen et al., 2017).

2.2 Supply Chain Coordination under Emission Constraints

Coordination among the supply chain insiders contributes to the sustainable performance and desirable profits of the supply chain (Jadhav et al., 2019). Jeuland and Shugan (1983) defined supply chain collaboration as a precise set of actions to achieve supply chain excellence, which requires the coordination of disparate incentives due to the rational entrepreneurs for individual optimality. Blome et al. (2014) found that coordination might result in substantial performance gains in sustainability if the supply chain pursued thoroughly and strategically. Xu et al. (2017) stated that cooperation in the supply chain realizes a quick response to the demand fluctuation, and it is, thus, effective to resolve the demand uncertainty. Kumar et al. (2023) defined the concept of supply chain decarbonization as reducing carbon emissions by establishing a net-zero carbon supply chain. They conducted a systematic literature review and argued that coordination enables end-to-end supply chain decarbonization. Koh et al. (2023) provided a meta-review on strategies for carbon neutrality through supply chain management, and pointed out that coordination among stakeholders is essential to achieve carbon mitigation. Liu et al. (2023) said that collaboration is an essential approach to reduce emissions in the entire supply chain. Researchers have proven that contracts possess desirable mechanistic features to create a cooperation incentive through a transfer payment scheme (Cachon, 2003). Many contracts have been provided for guiding the supply chain cooperation considering the environmental goals. Wang and Choi (2020c) compared the coordinated effectiveness of three contracts in a green supply chain, including revenue sharing contract, cost sharing contract, and two-part tariff contract. Hu et al. (2022) investigated the two-part tariff contract to coordinate the green supply chain with green awareness. He et al. (2023) considered bilateral participation contracts to achieve long-term cooperative emission reduction in a low-carbon supply chain. Chen et al. (2001) and Giri and Sarker (2017) discuss the supply chain coordination problem with warehousing contracts. A call option contract can be attributed to the originality since the solution difficulty results in the scarcity of option-coordinated studies in sustainability (Hong & Guo, 2019). Wang et al. (2018) and Wang and Choi (2020a, 2020b) explored the firm's option decisions individually without considering

coordination, which reduces their significance. Peng et al. (2020) proposed option contracts to coordinate low-carbon supply chains but without warehousing contracts. This paper fills the gaps and enriches research through dual-contract coordination with option and warehousing contracts.

Barratt (2004) highlighted the role of mutuality in supply chain coordination. Mutual benefits and risk-sharing arising from collaboration are vital to its success in initiating all the insiders. Some related literature works have taken into consideration the Pareto improvement to be closer to reality. Chen et al. (2014) confirmed that a Pareto option contract exists in the supply chain configuration, but they ignored the environmental responsibility that is considered in this research.

Accordingly, this paper analyses the Pareto conditions that ensure the contracts are performed with mutual benefits. Furthermore, synergistic benefits achievable through contracts are discussed by Newsvendor models, which are pinpointed by Cachon (2003) to be sufficiently rich to find out the available contracts for the collaboration problem. This paper also adopts Newsvendor models based on the work by Wang and Choi (2020a, 2020b) and Sana (2022a). Previous works used Lagrange optimization to find the local maxima or minima which is also adopted by this research. The difference is that Stackelberg steps are used to achieve a relationship of variables to build Lagrange constraints. This Lagrange-Stackelberg method is first used in literature and contributes to the novelty of this research.

All in all, this research builds its novelty by analyzing the Pareto-efficient supply chain coordination achievable through option and warehousing contracts considering the environmental responsibility, with the originality of a Lagrange-Stackelberg method to analytically solve this complicated problem. Demand uncertainty is better resolved by option characteristics and coordination. Customers' green awareness inspires green upgrades, which is essential to the success of the ETS.

III. MODEL FORMULATION AND PROBLEM SOLVING

Game-theoretic models considering decentralized, integrated and coordinated supply chains are built in this section, in which the Lagrange-Stackelberg process helps solve the risk-bearing collaboration problem with green-inclined customers and emission reduction targets under the ETS. Option and warehousing contracts are used for coordination and analytical results are given with option pricing and production/ordering decisions. This research assumes the manufacturer is the Stackelberg leader, as mentioned by Wang and Choi (2020c) that the manufacturer always dominates the market like Volkswagen and General Motors. The notations of the demand function, parameters, and decision variables are shown in Table 1.

Table 1. Notations

Notations for Demand Function			
	Demand function considering green awareness and uncertain demand, which	i	Green level resulted from the green investment.

$D(i, \varepsilon)$	is stochastic and differentiable. $D(i, \varepsilon) = y(i) + \varepsilon$.		
$y(i)$	Riskless demand function. $y(i) = a + bi$.	ε	Random variable related to uncertainty. $\varepsilon \in [A, B], E(\varepsilon) = \mu$. $A > -a$.
a	The market scales. $a > 0$.	$f(\cdot)$	Probability density function for uncertainty ε .
b	Green sensitivity to the demand. $b > 0$.	$F(\cdot)$	Distribution function for uncertainty ε , which is non-negative and invertible.
Notations for Parameters			
c	Unitary cost, excluding the emission cost.	s	Resell price of the spare emissions.
e	Emission level per unit production.	v_l	Inventory cost per unit unsold product in the integrated supply chain.
E	Emission price.	v_m	Inventory cost per unit unexercised product of the manufacturer.
g	Goodwill cost per unit product from the unsatisfied demand.	v_r	Inventory cost per unit unsold product of the retailer.
H	Cost factor of the green investment.	w	Wholesale price per unit product.
K	Emission cap under ETS.	λ	The Lagrange Multipliers.
p	Selling price per unit product.	η^2	The slack variables.
p_o	Option price per unit product.	x^+	Larger value comparing zero with x , $x^+ = \max(0, x)$.
Notations for Decision Variables			
i	Green investment efforts.	q_b	Product order quantity.
p_e	Option exercising price per unit product.	q_s^e	Spare emissions.
q	Total production quantity ordered.	q^e	Extra emissions needed.
q_o	Product option quantity.	r	Stocking factor when $q \geq 0$.

Some specific assumptions are given for establishing the proposed newsvendor models as follows:

Assumption 1: A two-stage supply chain of a single product does not consider the substitution effect and capacity limit.

Assumption 2: The demand is homogenous in its preference for green efforts.

An increasing riskless demand function $y(i) = a + bi$ is used, similar to the research works by Tsao et al. (2017), Ji et al. (2017) and Wang and Choi (2019). Hence, the demand function considering the green preference and uncertain demand is $D(i, \varepsilon) = y(i) + \varepsilon$, $\varepsilon \in [A, B], E(\varepsilon) = \mu$. $A > -a$.

Assumption 3: Green efforts bear an increasing marginal cost.

A quadratic function, Hi^2 , serves to quantify the green investment efforts for lowering the emission level of per unit production, based on the research works by Liu et al. (2012), Ji et al. (2017), Basiri and Heydari (2017), Yang and Chen (2018), and Wang and Choi (2020b). It is reasonable to develop

a convex cost over the green investment level with a quadratic pattern since the firm cannot infinitely reduce its emission level.

Assumption 4: Both the option and exercising prices are less than the wholesale price, $p_o < w$, and $p_e < w$, whereas the total cost of exercising one option is larger than the wholesale price, $p_o + p_e > w$.

The first half of this assumption is the motivation for a retailer to conduct an option contract, while the second is the motivation for a manufacturer to provide an option contract.

Assumption 5: The benefits from selling per unit spare emissions cannot exceed the cost of purchasing per unit emission credits, $s \leq E$.

This assumption ensures that the company cannot benefit from just trading emissions instead of production.

Assumption 6: The integrated supply chain would like to take on a lower inventory cost, i.e., $v_l = \min(v_m, v_r)$.

The integrated supply chain could choose vendor-managed inventory (VMI) or retailer-managed inventory (RMI) by comparing their inventory performance. It makes sense that the central manager would like to choose better warehousing which costs less.

3.1 Decentralized Model

Normally, each insider in a supply chain acts separately to achieve its individual optimality. In this decentralized model assuming M-Stackelberg game, the retailer decides the order quantity out of the green-inclined market demand, and the manufacturer schedules its batch production and emission strategy upon receiving the retailer's order. The emission strategy includes the emission selling/purchasing decision and the green investment decision. It acts as a benchmark model for this research. The development of this decentralized model is described below:

The profit function of the retailer is:

$$\Pi_R(q) = p \min[D, q] - wq - g[D - q]^+ - v_r[q - D]^+ \quad (1)$$

The profit function of the manufacturer is:

$$\Pi_M(i) = (w - c)q - Hi^2 - E[(e - i)q - K]^+ + s[K - (e - i)q]^+ \quad (2)$$

Under the manufacturer's profit function, $E[(e - i)q - K]^+$ refers to the cost of purchasing extra emission credits, while $s[K - (e - i)q]^+$ refers to the revenue from selling the spare emission. Either

$E[(e-i)q-K]^+$ or $s[K-(e-i)q]^+$ can occur, but not both. Thus, considering the emission conditions, $E[(e-i)q-K]^+$ or $s[K-(e-i)q]^+$, the manufacturer's profit function is separated as shown below:

(1) Purchasing extra emission credits, $E[(e-i)q-K]^+$.

The manufacturer's profit function, when extra emission credits are required for enough production, is shown below:

$$\begin{cases} \Pi_M(i) = (w-c)q - Hi^2 - E[(e-i)q-K]^+ \\ s.t. \quad K - (e-i)q < 0 \end{cases} \quad (3)$$

(2) Selling the spare emission credits, $s[K-(e-i)q]^+$.

The manufacturer's profit function, when the firm benefits from selling the spare emissions, is shown below:

$$\begin{cases} \Pi_M(i) = (w-c)q - Hi^2 + s[K-(e-i)q]^+ \\ s.t. \quad (e-i)q - K \leq 0 \end{cases} \quad (4)$$

The constraint $(e-i)q - K \leq 0$ also considers an extreme situation under which the firm just produces the emission-capped quantity, i.e., $(e-i)q - K = 0$.

3.1.1 Problem solving for the retailer's model

According to the M-Stackelberg steps, the retailer first decides its optimal order quantity provided the green investment efforts are known.

A stocking factor $r = q - y(i)$ is used based on the works by Wang and Choi (2019, 2020a, 2020b) and Petruzzi and Dada (1999). This riskless leftover can be compared with the demand uncertainty variable ε . If $r > \varepsilon$, product leftover occurs. If $r < \varepsilon$, demand faces a product shortage. Meanwhile, we define $\Lambda(r) = \int_A^r (r-x)f(x)dx$ for expected product leftover and $\Gamma(r) = \int_r^B (x-r)f(x)dx$ for the expected product shortage. The expected retailer's profit function can be built as follows:

$$\Pi_R(r) = (p-w)[y(i) + \mu] - (p-w+g)\Gamma(r) - (v_r + w)\Lambda(r) \quad (5)$$

From *Proof 1* in the Appendix, we have $r_D^* = F^{-1}\left(\frac{p-w+g}{p+g+v_r}\right)$. Then we have a relationship between

the order quantity q and the green investment efforts i , as: $q = a + bi + r_D^*$. To further solve this

decentralized problem, we combine this relationship with the manufacturer's profit model under each emission scenario.

3.1.2 Problem solving for the manufacturer's model over the emission cap

This scenario assumes that the manufacturer decides to produce more and purchase extra emission credits. Thus, it is constrained by the emission condition $K - (e - i)q < 0$. Based on the obtained relationship $q = a + bi + r_D^*$ and the analytical result $r_D^* = F^{-1}\left(\frac{p - w + g}{p + g + v_r}\right)$ above, we can write the expected manufacturer's profit function as below:

$$\begin{cases} \Pi_M(i) = [w - c - E(e - i)](a + bi + r_D^*) - Hi^2 + EK \\ s.t. \quad K - (e - i)(a + bi + r_D^*) < 0 \end{cases} \quad (6)$$

From *Proof 2* in the Appendix, we build the Lagrange function with the Lagrange Multipliers λ_1 and the slack variable η_1^2 which is used to satisfy the equality constraint required. The Karush-Kuhn-Tucker (KKT) conditions are widely used to solve the non-linear programming to get optimality, given the equality conditions are satisfied. According to the KKT conditions, the result under the emission cap requires $\lambda_1 = 0$. We achieve the decentralized results over the emission cap, as shown below:

$$\begin{cases} \lambda_1 = 0 \\ r_D^* = F^{-1}\left(\frac{p - w + g}{p + g + v_r}\right) \\ i_{Do}^* = \frac{E(a - be + r_D^*) + b(w - c)}{2(H - bE)} \\ q_{Do}^* = a + bi_{Do}^* + r_D^* \\ q_D^{e*} = (e - i_{Do}^*)q_{Do}^* - K \end{cases} \quad (7)$$

The profits of the retailer, the manufacturer, and the decentralized supply chain are Π_{DoR} , Π_{DoM} , and Π_{Do} , as shown in *Proof 2*.

Lemma 1.1: When $\lambda_1 = 0$, the decentralized supply chain achieves Π_{Do} profit through producing over the emission cap, where the retailer orders $a + bi_{Do}^* + r_D^*$ products that require the manufacturer to purchase $(e - i_{Do}^*)q_{Do}^* - K$ emission credits.

We have the best decentralized result over the emission caps, which will be compared with others (at and under the caps) to achieve the optimal result in the decentralized model.

3.1.3 Problem solving for the manufacturer's model under the emission cap

Under this scenario, production is scheduled within the emission limitation. The spare emissions are traded into the market for extra revenue. Thus, it is constrained by the emission condition $(e-i)q-K \leq 0$. From *Proof 3* in the Appendix, the decentralized results under the emission cap are shown below:

$$\begin{cases} \lambda_2 = 0 \\ r_D^* = F^{-1}\left(\frac{p-w+g}{p+g+v_r}\right) \\ i_{Du}^* = \frac{s(a-be+r_D^*)+b(w-c)}{2(H-bs)} \\ q_{Du}^* = a + bi_{Du}^* + r_D^* \\ q_{sD}^* = K - (e-i_{Du}^*)q_{Du}^* \end{cases} \quad (8)$$

The profits of the retailer, the manufacturer, and the decentralized supply chain are Π_{DuR} , Π_{DuM} , and Π_{Du} , as shown in *Proof 3*.

Lemma 1.2: When $\lambda_2 = 0$, the decentralized supply chain achieves Π_{Du} profit through producing under the emission cap, where the retailer orders $a + bi_{Du}^* + r_D^*$ products and the manufacturer can benefit from selling the $K - (e - i_{Du}^*)q_{Du}^*$ spare emissions.

We have the best decentralized result under the emission caps, which will be compared with others (over and under the caps) to achieve the optimal result in the decentralized model.

3.1.4 Problem solving for the manufacturer's model at the emission cap

This scenario is the specific situation mentioned above, the firm just produces the emission-limited quantity. From *Proof 4* in the Appendix, the decentralized results at the emission cap are:

$$\begin{cases} \eta_2 = 0 \\ r_D^* = F^{-1}\left(\frac{p-w+g}{p+g+v_r}\right) \\ i_{Da}^* = \sigma(r_D^*) \\ q_{Da}^* = \frac{K}{e-i_{Da}^*} \end{cases} \quad (9)$$

The profits of the retailer, the manufacturer, and the decentralized supply chain are Π_{DaR} , Π_{DaM} , and Π_{Da} , as shown in *Proof 4*.

Lemma 1.3: When $\eta_2 = 0$, the decentralized supply chain achieves Π_{Da} profit through producing at the emission cap, where the retailer orders $\frac{K}{e-i_{Da}}$ products that are the emission-limited quantity.

According to Lemmas 1.1, 1.2, and 1.3, the optimal profits with the best ordering and production strategy that producing over, under, or at the emission cap can be decided by comparing the supply chain profits of $(\Pi_{Do}, \Pi_{Du}, \Pi_{Da})$ in the decentralized supply chain if datasets are settled.

3.2 Integrated Model

Ideally, all the insiders in a supply chain act as one company with centrally concerted efforts for maximizing the collective interests. This pattern is rare but partially adopted by some industries, like the motor industry (Wang & Choi, 2020c). The integrated manner eliminates the decision discrepancies, as a central section makes an overall strategy instead of individual decisions. It acts as an idealized benchmark model for this research. The development of this integrated model is shown below:

(1) Purchasing extra emission credits, $E[(e-i)q - K]^+$.

The integrated profit function is:

$$\begin{cases} \Pi(q, i) = p \min[D, q] - cq - Hi^2 - g[D - q]^+ - v_l[q - D]^+ - E[(e-i)q - K]^+ \\ s.t. \quad K - (e-i)q < 0 \end{cases} \quad (10)$$

(2) Selling the spare emission credits, $s[K - (e-i)q]^+$.

$$\begin{cases} \Pi(q, i) = p \min[D, q] - cq - Hi^2 - g[D - q]^+ - v_l[q - D]^+ + s[K - (e-i)q]^+ \\ s.t. \quad (e-i)q - K \leq 0 \end{cases} \quad (11)$$

3.2.1 Problem solving for the integrated model over the emission cap

Based on the stocking factor $r = q - y(i)$, the expected integrated profit function over the emission cap can be built as follows:

$$\begin{cases} \Pi(r, i) = [p - c - E(e-i)](a + bi + \mu) - Hi^2 + E \cdot K \\ \quad - (p - c + g - E(e-i))\Gamma(r) - (v_l + c + E(e-i))\Lambda(r) \\ s.t. \quad K - (e-i)q < 0 \end{cases} \quad (12)$$

We achieve the integrated results over the emission cap (see *Proof 5*), as shown below:

$$\begin{cases} \lambda_3 = 0 \\ r_{lo}^* = F^{-1} \left(\frac{p - c + g - E(e - i_{lo}^*)}{p + g + v_l} \right) \\ i_{lo}^* \text{ by solving } \varpi(i) = 0 \\ q_{lo}^* = a + bi_{lo}^* + r_{lo}^* \\ q_l^{e*} = (e - i_{lo}^*)q_{lo}^* - K \end{cases} \quad (13)$$

The profit of the integrated supply chain is Π_{lo} , as shown in *Proof 5*.

Lemma 2.1: When $\lambda_3 = 0$, the integrated supply chain achieves Π_{lo} profit through producing over the emission cap, where the supply chain arranges $a + bi_{lo}^* + r_{lo}^*$ production and purchases $(e - i_{lo}^*)q_{lo}^* - K$ emission credits.

We have the best integrated result over the emission caps, which will be compared with others (at and under the caps) to achieve the optimal result in the integrated model.

3.2.2 Problem solving for the integrated model under the emission cap

Based on the stocking factor $r = q - y(i)$, the expected integrated profit function under the emission cap can be built as follows:

$$\begin{cases} \Pi(r, i) = [p - c - s(e - i)](a + bi + \mu) - Hi^2 + sK \\ \quad - (p - c + g - s(e - i))\Gamma(r) - (v_l + c + s(e - i))\Lambda(r) \\ s.t. \quad (e - i)q - K \leq 0 \end{cases} \quad (14)$$

We achieve the integrated results under the emission cap (See *Proof 6*), as shown below:

$$\begin{cases} \lambda_4 = 0 \\ r_{lu}^* = F^{-1} \left(\frac{p - c + g - s(e - i_{lu}^*)}{p + g + v_l} \right) \\ i_{lu}^* \text{ by solving } \vartheta(i) = 0 \\ q_{lu}^* = a + bi_{lu}^* + r_{lu}^* \\ q_{sl}^{e*} = K - (e - i_{lu}^*)q_{lu}^* \end{cases} \quad (15)$$

The profit of the integrated supply chain is Π_{lu} , as shown in *Proof 6*.

Lemma 2.2: When $\lambda_4 = 0$, the integrated supply chain achieves Π_{lu} profit through producing under the emission cap, where the supply chain arranges $a + bi_{lu}^* + r_{lu}^*$ production and benefits from selling the $K - (e - i_{lu}^*)q_{lu}^*$ spare emissions.

We have the best integrated result under the emission caps, which will be compared with others (over and under the caps) to achieve the optimal result in the integrated model.

3.2.3 Problem solving for the integrated model at the emission cap

This scenario is the specific situation mentioned above, the production just runs out of the free emissions. From *Proof 7* in the Appendix, we have the integrated results at the emission cap, as follows:

$$\begin{cases} \eta_4 = 0 \\ r_{la}^* = \frac{K}{e - i_{la}^*} - a - bi_{la}^* \\ i_{la}^* \text{ by solving } \Theta(i) \\ q_{Da}^* = \frac{K}{e - i_{la}^*} \end{cases} \quad (16)$$

The profit of the integrated supply chain is Π_{la} , as shown in *Proof 7*.

Lemma 2.3: When $\eta_4 = 0$, the integrated supply chain achieves Π_{la} profit through producing at the emission cap, where the supply chain arranges $\frac{K}{e - i_{la}^*}$ production, which is the emission-limited quantity.

According to Lemmas 2.1, 2.2, and 2.3, the optimal profits with the best ordering and production strategy that producing over, under, or at the emission cap can be decided by comparing the supply chain profits of $(\Pi_{lo}, \Pi_{lu}, \Pi_{la})$ in the integrated supply chain if datasets are settled.

3.3 Coordinated Model

Coordination can not only reduce the profit discrepancy but also help the polluting insiders better develop under the tightened emission regulations of the ETS. Under this scenario, the manufacturer designs a call option contract with option and exercising prices. Based on this the retailer decides its order quantity and option quantity out of uncertain demand. Besides the green investment efforts and emission strategy, the manufacturer needs to decide the exercising price given the option price is certain. This proposed option contract integrates the supply chain to facilitate the distribution of profits through pricing between both insiders. Besides, a warehousing contract is proposed, under which the supply chain members promise to adopt the warehousing with a lower inventory cost.

Since the proposed contracts make the retailer's decision-making more complicated, the expressions of the retailer's decisions cannot be constantly written. This paper first uses the Lagrangian method to settle the M-Stackelberg game. It regards the equality conditions resulting from the retailer's process as the Lagrange constraints for the subsequent manufacturer's decision-making problem, making it

possible to analytically solve this coordination problem. This coordinated model acts as the target model for this research. Its development is shown below:

The profit function of the retailer is:

$$\Pi_R(q_o, q) = p \min[D, q] - wq_b - p_o q_o - p_e [\min[D - q_b, q_o]]^+ - g[D - q]^+ - v_r^c [q - q_o - D]^+ \quad (17)$$

The profit function of the manufacturer is:

$$\begin{aligned} \Pi_M(p_e, i) = & wq_b + p_o q_o + p_e [\min[D - q_b, q_o]]^+ - cq - Hi^2 - v_m^c [q_o - [\min[D - q_b, q_o]]^+] \\ & - E[(e-i)q - K]^+ + s[K - (e-i)q]^+ \end{aligned} \quad (18)$$

To raise the whole profit to the integrated level, the production quantity (it is equal to the total order quantity in an MTO supply chain) and the green investment efforts should reach the integrated level. The production quantity is decided by the stocking factor r . Thus, this coordinated problem can use the results of the stocking factor r and the green investment efforts i under the corresponding emission scenario, namely, over, under, and at the emission cap.

Under the manufacturer's profit function, either $E[(e-i)q - K]^+$ or $s[K - (e-i)q]^+$ can occur, but not both. Thus, we separate the manufacturer's profit function considering the emission conditions, $E[(e-i)q - K]^+$ or $s[K - (e-i)q]^+$ as shown below:

(1) Purchasing extra emission credits, $E[(e-i)q - K]^+$.

The manufacturer's profit function is shown below:

$$\begin{cases} \Pi_M(p_e, i) = wq_b + p_o q_o + p_e [\min[D - q_b, q_o]]^+ - cq - Hi^2 \\ \quad - v_m^c [q_o - [\min[D - q_b, q_o]]^+] - E[(e-i)q - K]^+ \\ s.t. \quad K - (e-i)q < 0 \end{cases} \quad (19)$$

(2) Selling the spare emission credits, $s[K - (e-i)q]^+$.

$$\begin{cases} \Pi_M(p_e, i) = wq_b + p_o q_o + p_e [\min[D - q_b, q_o]]^+ - cq - Hi^2 \\ \quad - v_m^c [q_o - [\min[D - q_b, q_o]]^+] + s[K - (e-i)q]^+ \\ s.t. \quad (e-i)q - K \leq 0 \end{cases} \quad (20)$$

3.3.1 Problem solving for the retailer's model

Under the M-Stackelberg game, the manufacturer assumes that the retailer has decided its order and option quantity given the green investment efforts are known.

A stocking factor $r = q - y(i)$ is used. Also, we define $\Lambda_c(q_o, r) = \int_A^{r-q_o} (r - q_o - x)f(x)dx$ for expected product leftover, $\Omega(q_o, r) = \int_{r-q_o}^r (r - x)f(x)dx$ for expected option leftover, and $\Gamma(r) = \int_r^B (x - r)f(x)dx$ for the expected product shortage. Since this coordinated problem uses the integrated results of r and i under the corresponding emission scenario, the retailer's profit function can be written as:

$$\begin{aligned} \Pi_R(q_o) = & (p - w)[y(i) + \mu] - (p - w + g)\Gamma(r) - (w + v_r^c)\Lambda_c(q_o, r) - (w - p_e)\Omega(q_o, r) \\ & - (p_o + p_e - w)q_o - (w - p_e)q_o \int_A^{r-q_o} f(x)dx \end{aligned} \quad (21)$$

From *Proof 7*, we have $(v_r^c + p_e) \int_A^{r-q_o} f(x)dx - (p_o + p_e - w) = 0$. This relationship will be used as the Lagrange constraints to solve the manufacturer's decision problem.

3.3.2 Problem solving for the manufacturer's model over the emission cap

This scenario adopts the integrated results of r_{lo}^* and i_{lo}^* , which ensures that $K - (e - i)q < 0$ is constantly built. Then, we can write the expected manufacturer's profit function as below:

$$\begin{cases} \Pi_M(q_o, p_e) = [w - c - E(e - i)][y(i) + \mu] + EK - Hi^2 \\ \quad - (w - p_o + v_m^c)q_o + [w - c - E(e - i) - v_m^c - p_e]\Omega \\ \quad + [w - c - E(e - i)]\Lambda_c - [w - c - E(e - i)]\Gamma \\ \quad + [w - c - E(e - i)]q_o \int_A^{r-q_o} f(x)dx + (p_e + v_m^c)q_o \int_{r-q_o}^B f(x)dx \\ s.t. \quad (v_r^c + p_e) \int_A^{r-q_o} f(x)dx - (p_o + p_e - w) = 0 \end{cases} \quad (22)$$

The coordinated results over the emission cap are shown below (See *Proof 9*):

$$\begin{cases} r_{Co}^* = r_{lo}^* \\ i_{Co}^* = i_{lo}^* \\ q_{oCo}^* = r_{Co}^* - F^{-1}\left(\frac{p_o + p_{eCo}^* - w}{v_r^c + p_{eCo}^*}\right) \\ p_{eCo}^* \text{ by solving } \Phi(p_e) \\ q_{Co}^* = a + bi_{Co}^* + r_{Co}^* \\ q_{bCo}^* = q_{Co}^* - q_{oCo}^* \\ q_C^{e*} = (e - i_{Co}^*)q_{Co}^* - K \end{cases} \quad (23)$$

The profits of the retailer, the manufacturer, and the coordinated supply chain are Π_{CoR} , Π_{CoM} , and Π_{Co} , as shown in *Proof 9*.

Lemma 3.1: The coordinated supply chain achieves Π_{Co} profit through producing over the emission cap, where the retailer orders $a + bi_{Co}^* + r_{Co}^*$ products that require the manufacturer to purchase $(e - i_{Co}^*)q_{Co}^* - K$ emission credits. The retailer decides to procure q_{oCo}^* options and will exercise them with p_{eCo}^* exercising price when the uncertain demand is resolved.

As $v_I = \min(v_m, v_r)$, if the supply chain members adopt the proposed warehousing contract with $v_m^c = v_r^c = v_I$, we have $\Pi_{Co} = \Pi_{Io}$, as shown in *Proof 7*. The supply chain can be fully coordinated by the option and warehousing contracts. Without the warehousing contract, the coordinated supply chain bears more inventory cost than the integrated one out of $v_m^c \neq v_r^c$.

We have the best coordinated result over the emission caps, which will be compared with others (at and under the caps) to achieve the optimal result in the coordinated model.

3.3.3 Problem solving for the manufacturer's model under the emission cap

This scenario adopts the integrated results of r_{lu}^* and i_{lu}^* , which ensures that $(e - i)q - K < 0$ is constantly built. We achieve the coordinated results under the emission cap (See *Proof 10*), as shown below:

$$\begin{cases} r_{Cu}^* = r_{lu}^* \\ i_{Cu}^* = i_{lu}^* \\ q_{oCu}^* = r_{Cu}^* - F^{-1}\left(\frac{p_o + p_{eCu}^* - w}{v_r^c + p_{eCu}^*}\right) \\ p_{eCu}^* \text{ by solving } \Upsilon(p_e) \\ q_{Cu}^* = a + bi_{Cu}^* + r_{Cu}^* \\ q_{bCu}^* = q_{Cu}^* - q_{oCu}^* \\ q_{sC}^{e*} = K - (e - i_{Cu}^*)q_{Cu}^* \end{cases} \quad (24)$$

The profits of the retailer, the manufacturer, and the coordinated supply chain are Π_{CuR} , Π_{CuM} , and Π_{Cu} , as shown in *Proof 10*.

Lemma 3.2: The coordinated supply chain achieves Π_{Cu} profit through producing under the emission cap, where the retailer orders $a + bi_{Cu}^* + r_{Cu}^*$ products and the manufacturer can benefit from selling the $K - (e - i_{Cu}^*)q_{Cu}^*$ spare emissions. The retailer decides to procure q_{oCu}^* options and will exercise them with p_{eCu}^* exercising price when the uncertain demand is resolved.

As $v_I = \min(v_m, v_r)$, if the supply chain members adopt the proposed warehousing contract with $v_m^c = v_r^c = v_I$, we have $\Pi_{Cu} = \Pi_{lu}$, as shown in *Proof 8*. The supply chain can be fully coordinated by

the option and warehousing contracts. Without the warehousing contract, the coordinated supply chain bears more inventory cost than the integrated one out of $v_m^c \neq v_r^c$.

We have the best coordinated result under the emission caps, which will be compared with others (over and under the caps) to achieve the optimal result in the coordinated model.

3.3.4 Problem solving for the manufacturer's model at the emission cap

This scenario adopts the integrated results of r_{la}^* and i_{la}^* , which ensures that $(e-i)q-K=0$ is constantly built. From *Proof 11*, the coordinated results at the emission cap are obtained as follows:

$$\begin{cases} r_{Ca}^* = r_{la}^* \\ i_{Ca}^* = i_{la}^* \\ q_{oCa}^* = r_{Ca}^* - F^{-1}\left(\frac{p_o + p_{eCa}^* - w}{v_r^c + p_{eCa}^*}\right) \\ p_{eCa}^* \text{ by solving } X(p_e) \\ q_{Ca}^* = \frac{K}{e - i_{Ca}^*} \\ q_{bCa}^* = q_{Ca}^* - q_{oCa}^* \end{cases} \quad (25)$$

The profits of the retailer, the manufacturer, and the coordinated supply chain are Π_{CaR} , Π_{CaM} , and Π_{Ca} , as shown in *Proof 11*.

Lemma 3.3: The coordinated supply chain achieves Π_{Ca} profit through producing at the emission cap,

where the retailer orders $\frac{K}{e - i_{Ca}^*}$ products that are the emission-limited quantity. The retailer decides to procure q_{oCa}^* options and will exercise them with p_{eCa}^* exercising price when the uncertain demand is resolved.

According to Lemmas 3.1, 3.2, and 3.3, the optimal profits with the best ordering and production strategy that producing over, under, or at the emission cap can be decided by comparing the supply chain profits of $(\Pi_{Co}, \Pi_{Cu}, \Pi_{Ca})$ in the coordinated supply chains if datasets are settled.

We have the best supply chain profits over, under, and at the emission, as $(\Pi_{Do}, \Pi_{Du}, \Pi_{Da})$, $(\Pi_{Io}, \Pi_{Iu}, \Pi_{Ia})$, and $(\Pi_{Co}, \Pi_{Cu}, \Pi_{Ca})$, in the decentralized, integrated, and coordinated supply chains, respectively. Due to the implicit solutions, it is hard to achieve the optimal one through mathematical formulas without numerical values. However, we can compare them if the datasets are well-prepared.

As $v_I = \min(v_m, v_r)$, if the supply chain members adopt the proposed warehousing contract with $v_m^c = v_r^c = v_I$, we have $\Pi_{Ca} = \Pi_{Ia}$, as shown in *Proof 9*. The supply chain can be fully coordinated by

the option and warehousing contracts. Without the warehousing contract, the coordinated supply chain bears more inventory cost than the integrated one out of $v_m^c \neq v_r^c$.

Proposition 1: The option contract can fully coordinate the supply chain combined with the warehousing contract, otherwise partly coordinate the supply chain due to a bit higher inventory cost as $v_m^c \neq v_r^c$.

If $\Pi_R^C \geq \Pi_R^D$ and $\Pi_M^C \geq \Pi_M^D$, the coordinated model reaches Pareto improvement, which is determined by the profit-sharing-related parameters, including the wholesale price w and the option price p_o . Since it is hard to analytically express the Pareto-efficient conditions out of the complicated results, this research will conduct an in-depth discussion in the following Numerical Analysis section.

Proposition 2: The Pareto-improvement conditions are determined by the profit-sharing-related parameters, including the wholesale price w and the option price p_o .

IV. NUMERICAL ANALYSIS AND DISCUSSION

The Chinese fertilizer industry is considered a heavy carbon emitter and hence bears many social responsibilities and legal obligations in cutting emissions for sustainability. Therefore, the data collected from the Chinese phosphate fertilizer industry, as shown in Table 2, are used in this numerical study.

Table 2. Data Values

p	w	c	e	K	E	s	g	H	v_m	v_r	p_o
400	300	200	0.9	80	10	5	10	50000	10	5	100
USD	USD	USD	--	100ton	USD	USD	USD	USD	USD	USD	USD

We assume that the green-inclined demand function follows $y(i)=200+50i$ according to the market information, while the demand risk follows a normal distribution with $\mu=50$ and $\sigma=100$, where $\mathcal{E} \in [-\infty, \infty]$. As $v_m^c = v_r^c = v_l = \min(v_m, v_r)$, we have $v_m^c = v_r^c = v_l = 5$.

Numerical and sensitivity analyses will be conducted with discussion to derive managerial insights at the strategic and operational levels, as well as the awareness of win-win incentives to achieve high performances of low-carbon processing.

4.1 Numerical Results

Given the data set above, the ordering and production strategies are numerically addressed in Table 3.

Table 3. Numerical Results

	Unit	DSC			ISC	CSC		
		Retailer	Manufacturer	Total	Total	Retailer	Manufacturer	Total
Emission reduction level	--	0.1154			0.1214	0.1214		
Investment efforts	1000USD	66.5858			73.6898	73.6898		
Production quantity	100ton	192.9866			252.8782	252.8782		
Option quantity	100ton	--			--	74.0531		
Order quantity	100ton	192.9866			252.8782	178.8251		
Wholesale price	USD/ton	300			300	300		
Total cost (exercising option)	USD/ton	--			--	338.8509		
Option price	USD/ton	--			--	100		
Exercising price	USD/ton	--			--	238.8509		
Extra emission credits	100ton	71.4220			116.8923	116.8923		
Spare emissions	100ton	--			--	--		
Profits	1000USD	1198.2251	1791.8861	2990.1112	3273.5676	1274.4339	1999.1337	3273.5676
Strategy	--	over the emission cap			over the emission cap	over the emission cap		
Coordination	$v_m^c = v_r$	Profit loss			Maximum	Full Pareto-efficient coordination		

All the supply chain scenarios prefer to produce over the emission cap with purchasing extra emission credits. The joint option and warehousing contracts can surge the decentralized supply chain profit to the integrated level, where both the manufacturer and retailer benefit from the profit rise. Pareto-efficient coordination is achieved, under which both players are willing to perform the contracts. The higher potential profits inspire the manufacturer to invest more in emission reduction, from the decentralized 0.1154 to the integrated/coordinated 0.1214. This green effort, therefore, attracts more customers. More quantity is produced in the integrated and coordinated supply chain. As the option price is much lower than the wholesale price, the retailer tends to order fewer quantities with a higher option quantity. Its proportion depends on the exercising price decided by the manufacturer. The total cost of exercising one option is larger than the wholesale price. Due to the warehousing contract $v_m^c = v_r^c = v_f$, the supply chain can be fully coordinated.

4.2 Analysis of Sensitivity to the market

This section highlights the Pareto-efficient coordination under different markets with various emission conditions. Trends of profit and strategy are demonstrated with increasing demand uncertainties, green sensitivities, emission caps, and emission prices. For the production strategy in the right-top corner (b) of Figures 1.1-6.1, 1 refers to producing under the emission cap; 2 refers to producing at the emission cap; 3 refers to producing over the emission cap.

From Figure 1.1, the dual-contract coordination can reach integrated profits under demand uncertainty of 4, after which, its coordination ability cannot work as its production strategy changes from over to at the emission cap, same as the decentralized decisions (see (a) and (b)). Under 4, both insiders can benefit from option-enabled coordination (see (c) and (d)). The joint option and warehousing contracts fully coordinate the supply chain with Pareto improvement but cannot significantly function against higher risks. Figure 1.2 shows that the decentralized supply chain loses some quantity facing higher demand risks, but the integrated/coordinated supply chain does not (see (a)). Due to the increasing customer surplus, they would like to put greater efforts into cutting emissions (see (b) and (c)). The manufacturer would slightly raise its exercising price (see (d)).

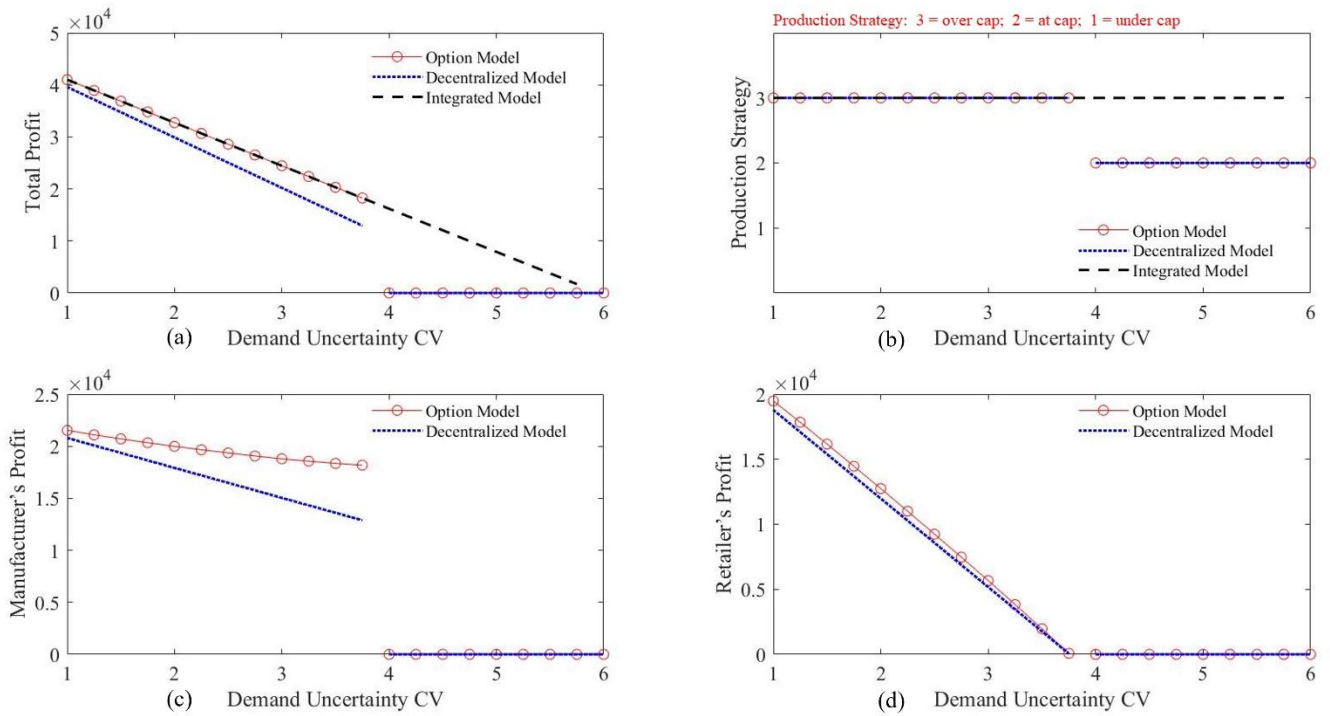


Figure 1.1 Profit trends with demand uncertainty CV

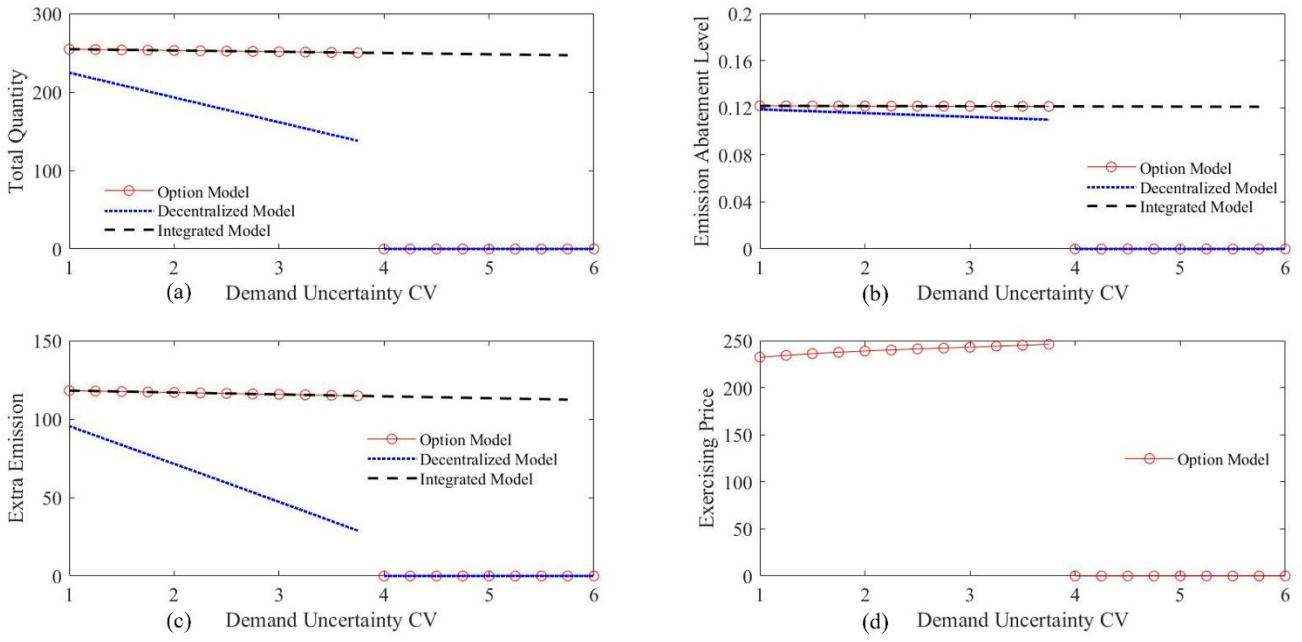


Figure 1.2 Quantity and emission trends with demand uncertainty CV

Alt Text: Figure 1.1 explains that the profits of the supply chain, the manufacturer, and the retailer decrease. The production strategy changes from 3 to 2. Figure 1.2 shows that quantity, emission abatement level, and extra emission decline, and the exercising price increases.

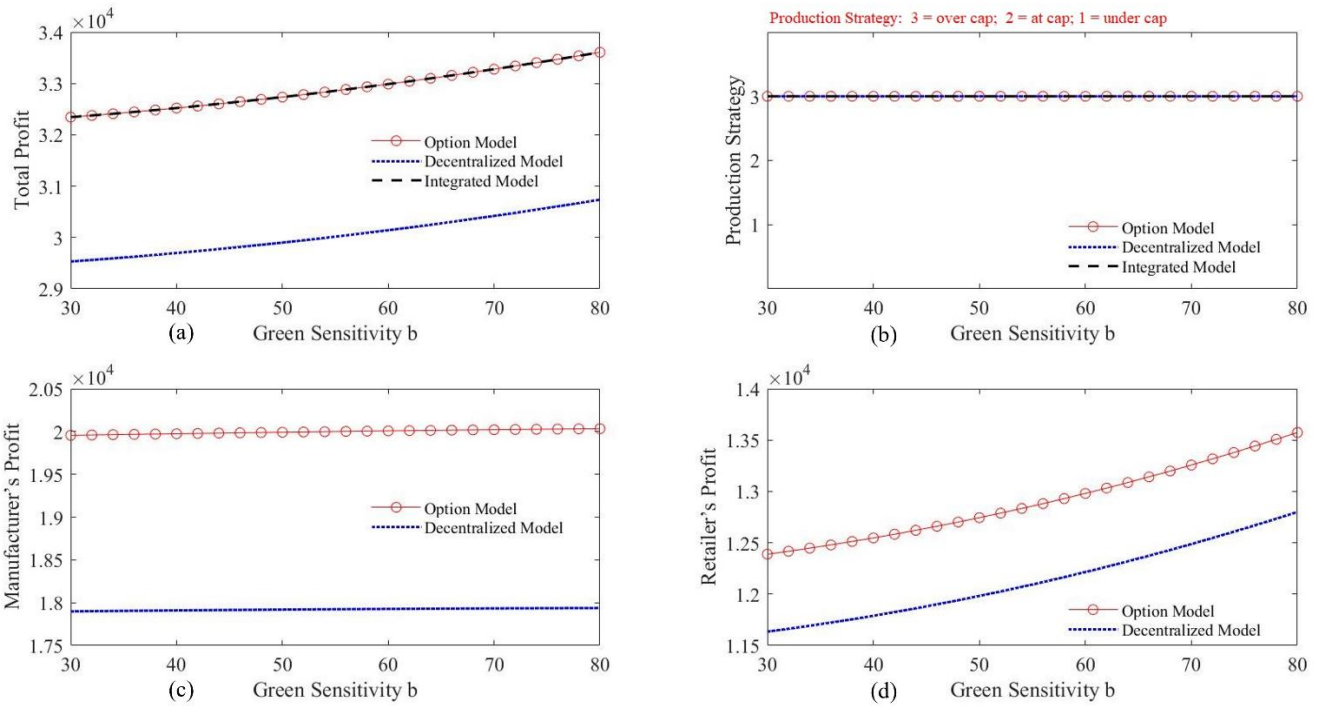


Figure 2.1 Profit trends with green sensitivity b

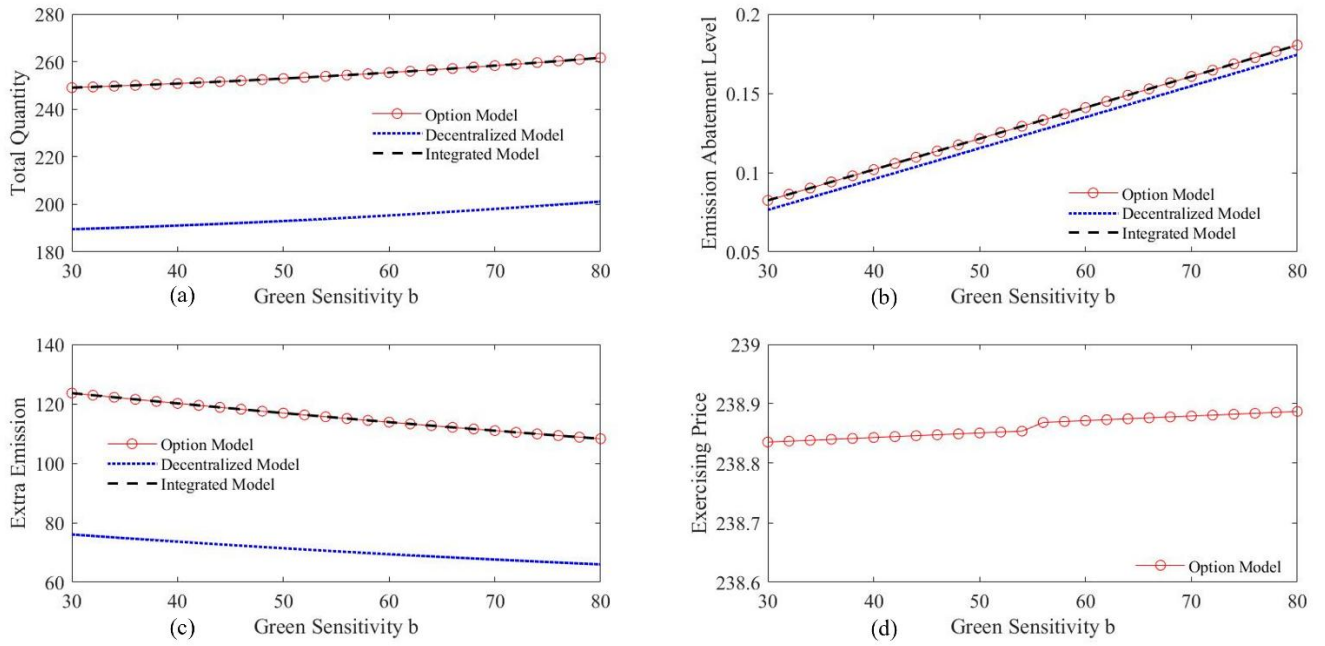


Figure 2.2 Quantity and emission trends with green sensitivity b

Alt Text: 2(a) explains that the profits of the supply chain, the manufacturer, and the retailer increase. The production strategy remains at 3. 2(b) shows that quantity, emission abatement level, and the exercising price increase, but the extra emission decreases.

Figure 2.1 confirms the role of green awareness in promoting the low-carbon economy. Both insiders' profits grow in line with the Pareto-efficient coordination through the dual contracts (see (c) and (d)). Obviously, the dual contracts can fully coordinate the supply chain and drive the decentralized profit to the integrated one (see (a)). Considering different green awareness, the production strategy will not change and remain at 3 (over the cap) for optimality (see (b)). In Figure 2.2, the emission abatement level experiences a marked rise (see (b)). Thus, fewer extra emission credits are required due to the emission reduction efforts (see (c)), although the total quantity increases with growing green awareness (see (a)). The exercising prices rise with increasing green awareness since green-aware customers would like to pay higher prices for green products.

From Figure 3.1, the supply chain can reach Pareto improvement and full coordination through the option and warehousing contracts (See (a), (c), and (d)). Figure 3.1 (a) says that stringent emission caps have a cost but can increase the green investment for sustainability shown in Figure 3.2 (b). The decentralized supply chain lifts its emission abatement level when the emission cap is less than 153 (Figure 3.1(b)). The integrated and coordinated supply chains are more sensitive to the emission regulations and will put efforts into emission reduction once the cap is 201. Due to the changes in production strategy, extra emissions are required over 151.5 in the decentralized model, and over 197 in the integrated and coordinated models (see Figure 3.2 (c)). Correspondingly, we can see that the

total quantity of the decentralized supply chain experiences a small drop at 151.5 and remains stable at 153, while it slightly rises at 197 and then remains stable at 201 in the integrated/controlled supply chain (see (a)). The exercising price changes between 197 and 201, and it remains stable before 197 and after 201. However, the exercising price slightly increases after 201 compared to that before 197 (see (d)).

Figure 4.1 also proves the coordination ability of the dual contracts to realize synergistic benefits with growing emission prices. The whole supply chain and manufacturer's profits decrease (see (a) and (c)), while the retailer's profit increases when the emission prices go up (see (d)). The production strategy remains at 3 (over emission cap) with increasing emission prices (see (b)). In Figure 4.2, the emission price does not affect the total quantity of the decentralized supply chain, while the integrated/controlled supply chain will achieve less quantity with increasing emission prices (see (a)). Higher emission prices encourage manufacturers to invest more in green upgrades (see (b)). Obviously, fewer extra emissions are required with the increasing emission costs (see (c)). Exercising prices remain stable from 239 to 238 (see (d)).

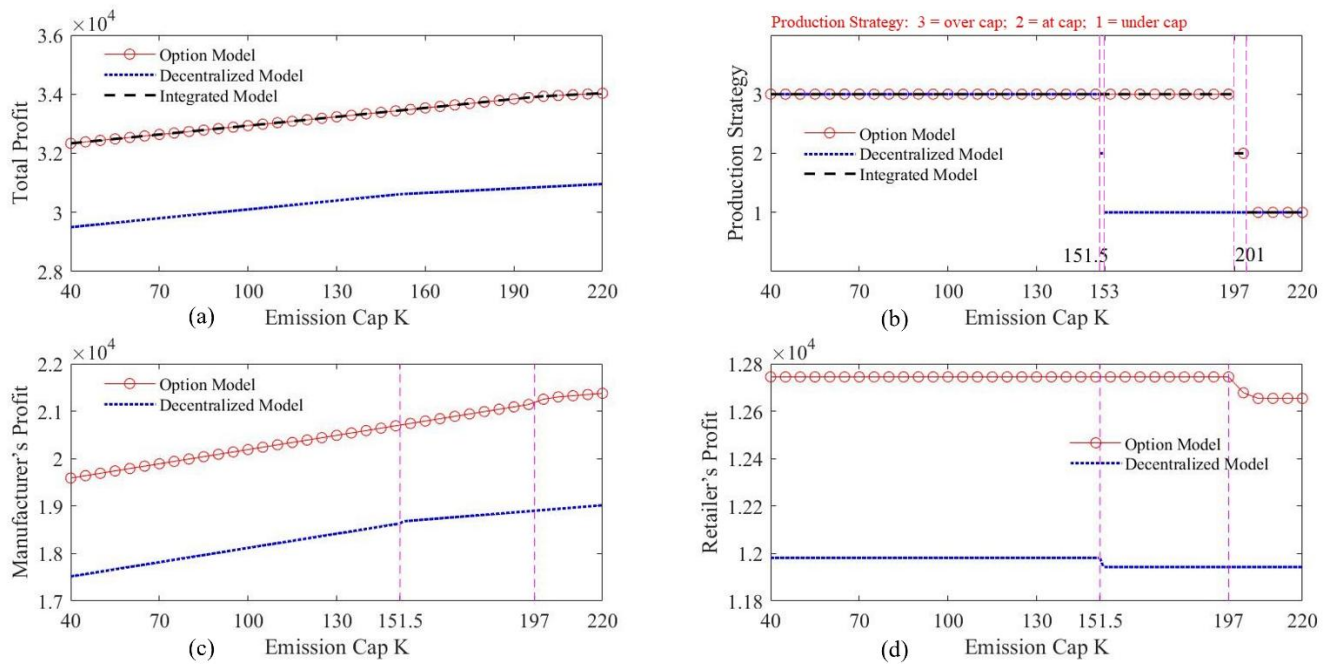


Figure 3.1 Profit trends with emission cap K

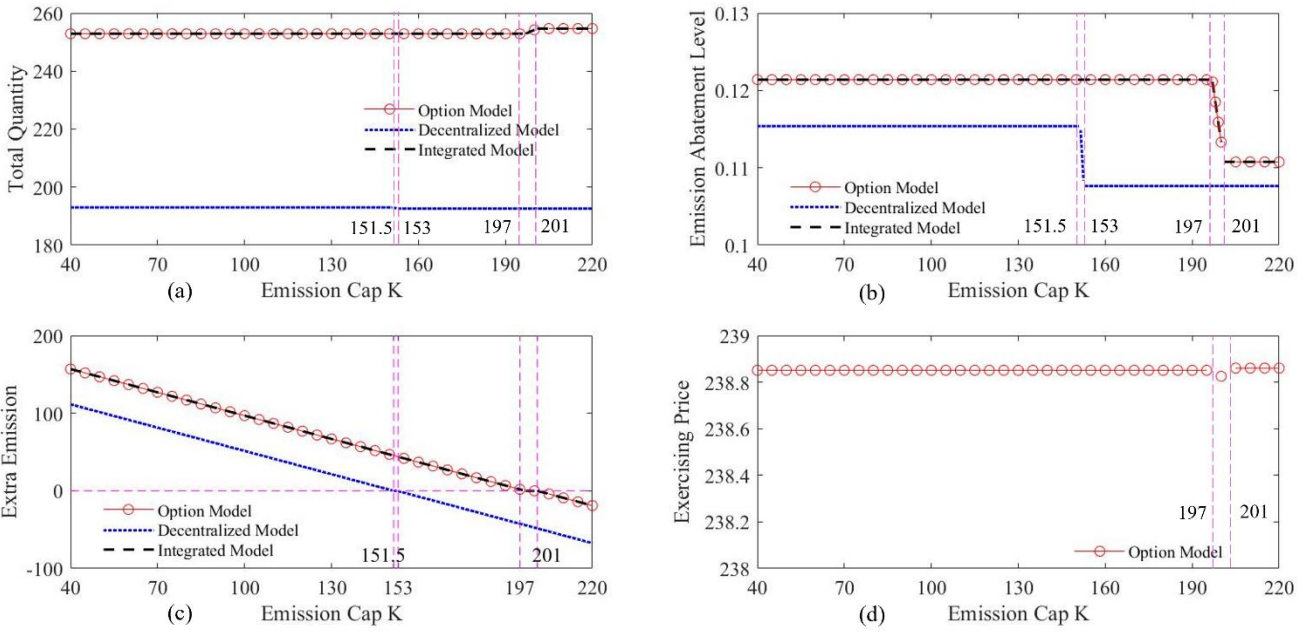


Figure 3.2 Quantity and emission trends with emission cap K

Alt Text: Figure 3.1 explains that the profits of the supply chain, the manufacturer, and the retailer increase. The production strategy changes from 3 to 2, then to 1. Figure 3.2 shows that quantity remains stable. The mission abatement level first remains stable then decreases, and the extra emission declines. The exercising price remains stable.

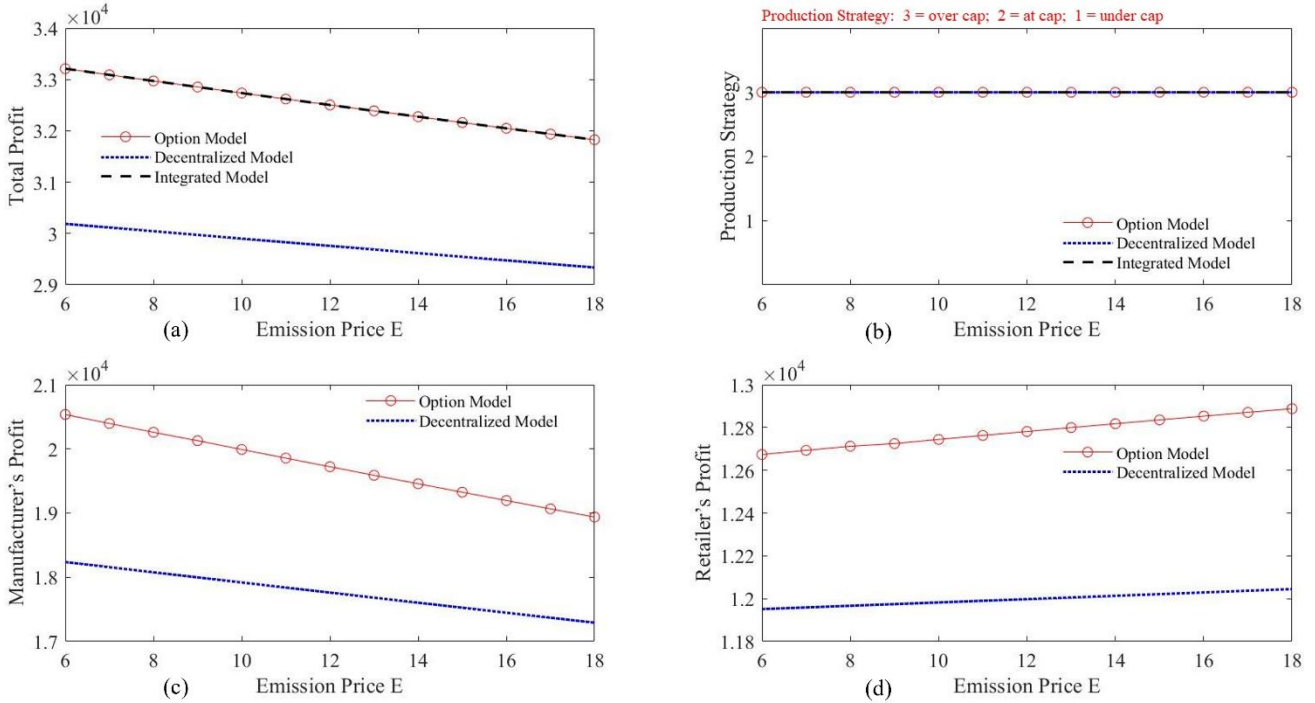


Figure 4.1 Profit trends with emission price E

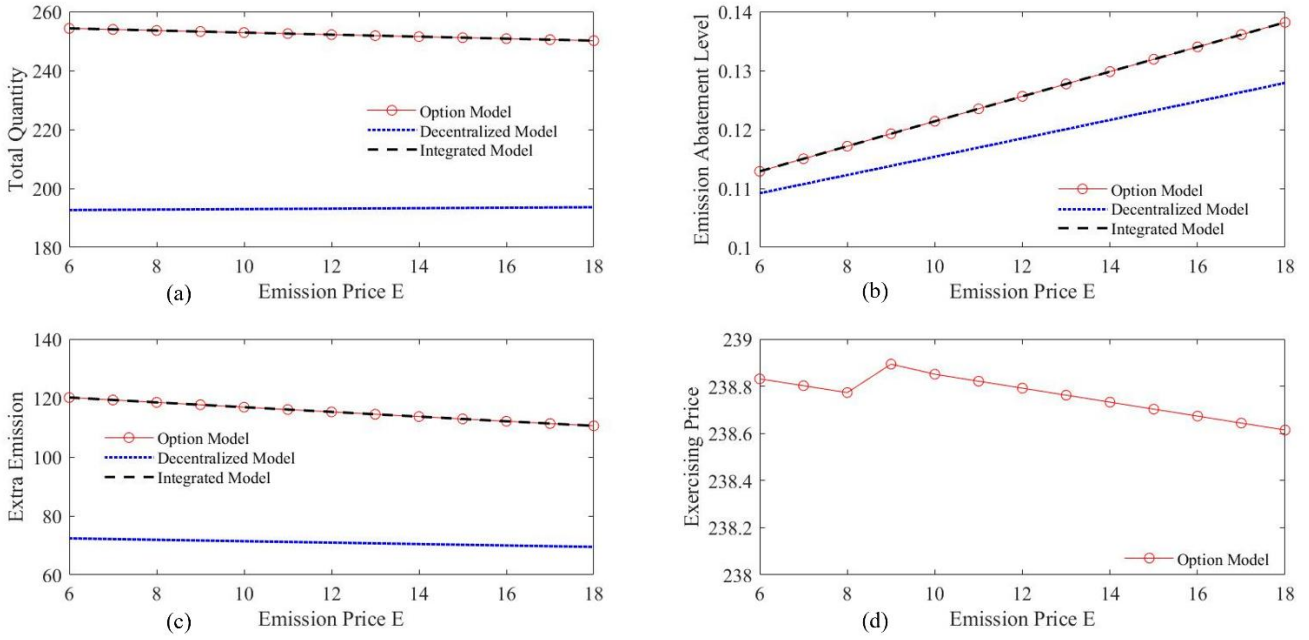


Figure 4.2 Quantity and emission trends with emission price E

Alt Text: Figure 4.1 explains that the profits of the supply chain and the manufacturer decrease but that of the retailer increases. The production strategy remains at 3. Figure 4.2 shows that quantity, the extra emission and emission price decrease but the emission abatement level increases.

4.3 Analysis of Sensitivity to the option contract

This section elaborates on the profit and strategy trends when the wholesale price and option price vary.

In Figure 5.1, the dual contracts fully coordinate the supply chain, and its profits remain stable with increasing wholesale prices (see (a), (c), and (d)). Yet the decentralized supply chain experiences a drop in profits. The total quantity and extra emissions show a similar trend in Figure 5.2 (see (a) and (c)). However, the manufacturer in the decentralized model can set a lower wholesale price at 207.6, but at 213 in the coordinated model (see Figure 5.1(c)). After 213, both supply chain insiders can enjoy increasing revenue via the option contract. The manufacturer's profit increases and the retailer's profit decreases when the wholesale price rises (see Figure 5.1(c) and (d)). The green efforts remain stable without being close to the wholesale price after 213, while the exercising price edges up after 213 (see Figure 5.2(b) and (d)). The production strategy remains at 3 (over the cap) in the decentralized supply chain, while it changes from 2 (at the cap) to 3 (over the cap) at the point of 207.6 and 213 in the integrated and coordinated supply chain, respectively.

From Figure 6.1, the option price should be set within 26.4 and 129 to achieve the Pareto-efficient coordination (see (a), (c), and (d)). The manufacturer gains from a higher option price, while the retailer's profits drop with the growing option prices (see (c) and (d)). The production strategy will not change with increasing option price and remains at 3 (over the emission cap). In Figure 6.2, option

prices will not influence the total quantity, and the coordinated/integrated supply chain obtains more quantity than the decentralized one (see (a)). The green investment level is not changed by different option prices, but the option contract enables a higher green level, the same as the integrated one, than the decentralized level (see (b)). A similar trend is presented in extra emissions (see (c)). The exercising price dramatically decreases (see (d)) since the total cost of exercising one option cannot be too high compared with the wholesale price.

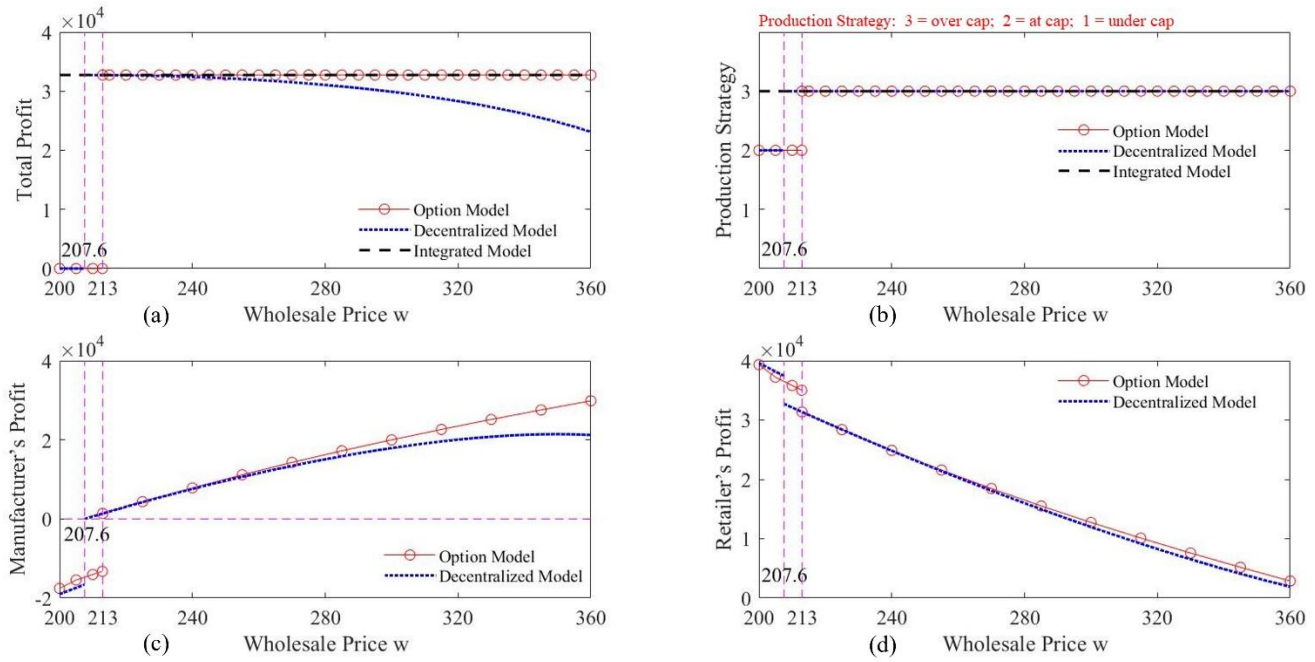


Figure 5.1 Profit trends with wholesale price w

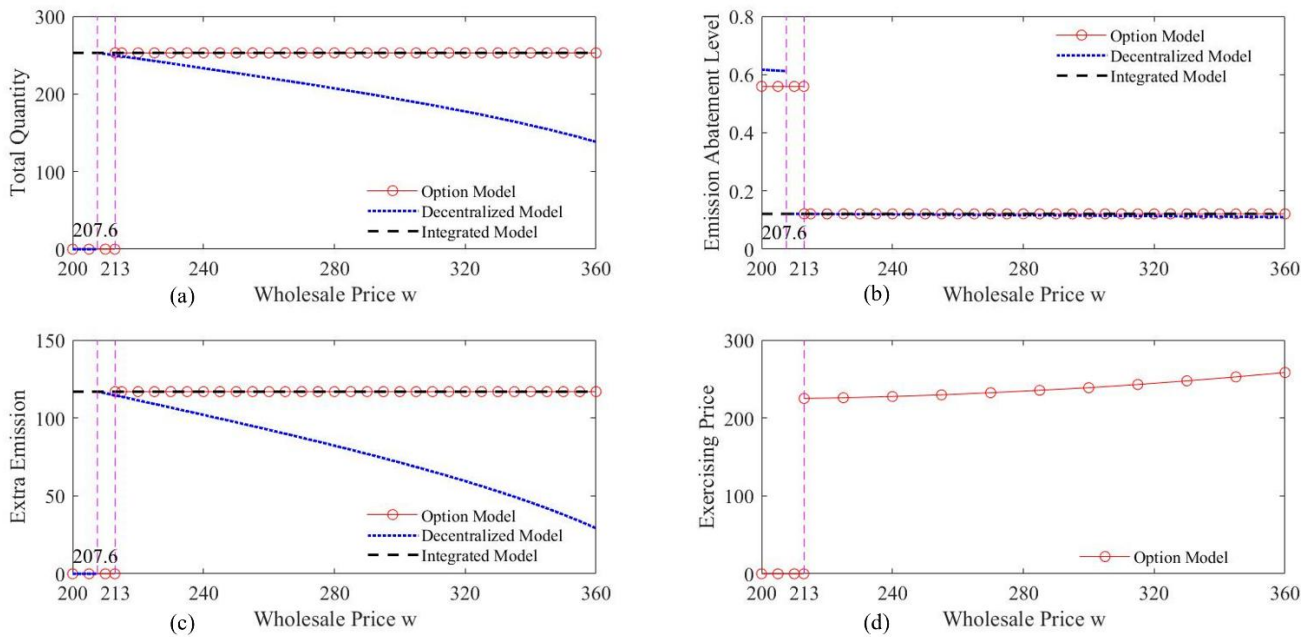


Figure 5.2 Quantity and emission trends with wholesale price w

Alt Text: Figure 5.1 explains that profits of the supply chain and the retailer decrease but the profit of the manufacturer increases. The production strategy changes from 2 to 3. Figure 5.2 shows that quantity, the extra emission and emission abatement level decrease but the emission price increases.

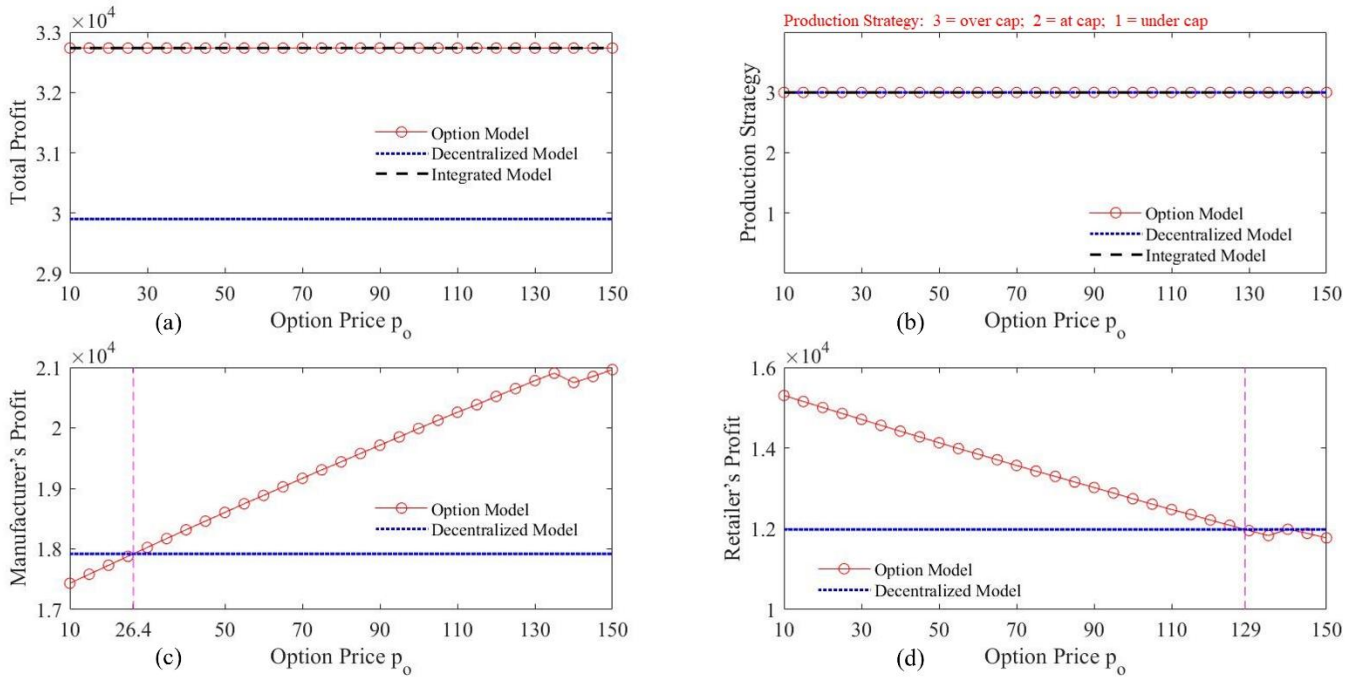


Figure 6.1 Profit trends with option price p_o

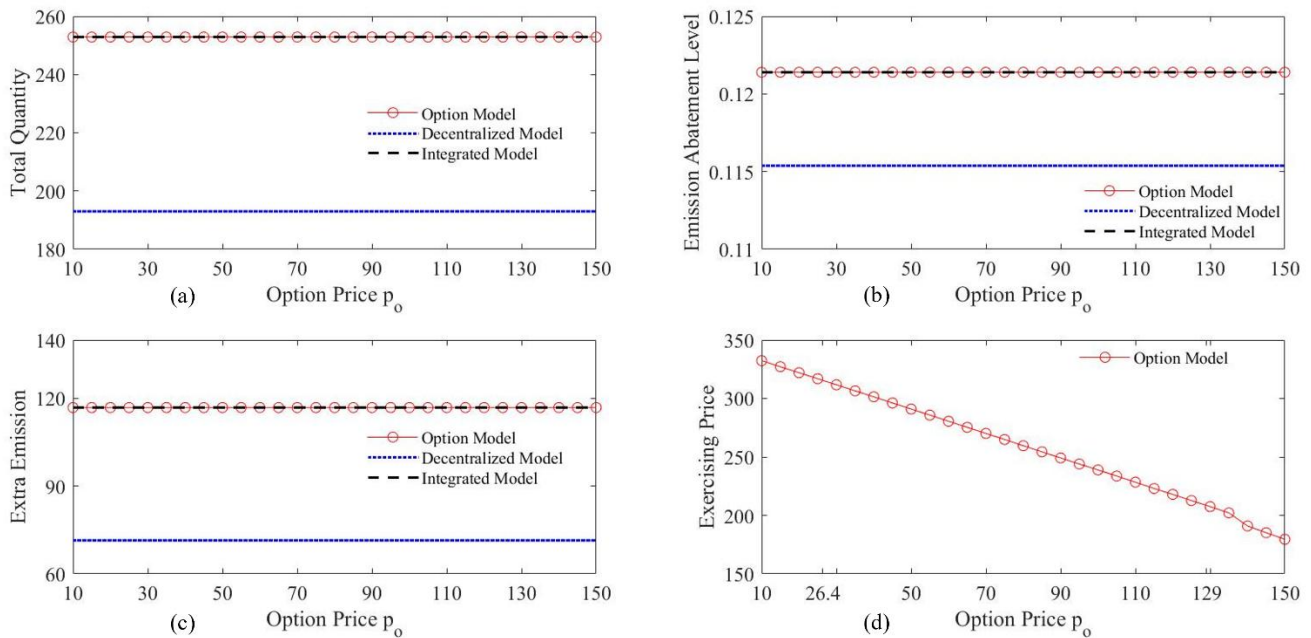


Figure 6.2. Quantity and emission trends with option price p_o

Alt Text: Figure 6.1 explains that the profits of the supply chain remain stable. The profit of the manufacturer increases of that of the retailer declines. The production strategy remains at 3. Figure

6.2 shows that quantity, the extra emission and emission abatement level remain stable but the emission price decreases.

4.4 Discussion and Managerial Insights

From the analyses above, we can achieve the following findings: (1) the proposed Lagrange-Stackelberg method can efficiently help the supply chain insiders make better decisions, including contract settings under the ETS; (2) the inventory cost of each insider determines whether the option contract can fully or partially coordinate the supply chain. Hence, the supply chain and its members can achieve optimal profitability through dual-contract coordination by option and warehousing contracts; (3) the joint option and warehousing contract can fully achieve Pareto-efficient coordination but cannot significantly function against higher risks. Producing over the emission cap is the best in most cases, and the ordering strategy mainly depends on the demand uncertainty and price factors; (4) green investment is vital to thrive under emission constraints. The increasing green awareness notably inspires emission reduction, which leads to greater efforts due to the correspondingly rising customer surplus. (5) The stringent emission caps and the increase in emission prices have a cost but can increase the green investment for sustainability. The policy-makers should weigh both for building a healthy low-carbon environment; (6) Both option and wholesale prices essentially determine the Pareto-efficient coordination through profit sharing. The contract-maker should deliberate on its contract settings to bring this contract to fruition.

Accordingly, we have the following managerial insights for the supply chain and suggestions for the policy-makers to develop the economy under a sustainable emission market.

Managerial Insight 1: The supply chain members can achieve desirable profits by coordination through option and warehousing contracts. The supply chain can be fully coordinated with a joint option and warehousing contract, and partially coordinated only by an option contract.

Managerial Insight 2: Under the ETS, purchasing extra carbon emissions performs better in most cases, and thus the investment in green upgrades is vital for the supply chain members to thrive with emission constraints.

Managerial Insight 3: The contract-maker should deliberate its contract settings including the option and wholesale prices, as well as warehousing, to develop Pareto-efficient coordination.

Managerial Insight 4: The stringent ETS system settings effectively drive sustainability which carries a cost. Increasing green awareness acts as an incentive for low-carbon investment, which correspondingly leads to higher profitability and emission mitigation.

The policy-makers should weigh both the emission caps and the emission prices for shaping a sustainably low-carbon market. Moreover, intervening to influence consumer demand on green-

labelled products may be a challenging but more efficient way of achieving both profitability and sustainability.

V. CONCLUSION

This research builds its novelty by analyzing the Pareto-efficient coordination achievable through a joint option and warehousing contract considering the environmental responsibility, with the originality of the Lagrange-Stackelberg optimization to analytically solve this complicated problem. Analytically solving this complicated coordination problem requires appropriate mathematical tools, so that a new method that combines the Lagrangian process with the Stackelberg game is proposed with demand uncertainty and emission constraints.

This research reveals that the proposed option and warehousing contracts are capable of full coordination. Otherwise, partial coordination also raises profitability only by the option contract. The option price and wholesale price determine both the profit sharing and the Pareto-efficient coordination, and thus the contract-maker should deliberate both in its contract settings. The warehousing contract decides the degree of coordination so that warehousing is another consideration upon building contracts. Based on the discussion of ordering strategy under different markets and contract settings, it shows that the ordering strategy mainly depends on demand uncertainty and price factors. Producing over the emission cap is the best in most cases. Besides the increasing green awareness, the stringent emission caps and the increase in emission prices can increase green investment for sustainability, even if they cost some. The policy-makers should weigh both for building a healthy low-carbon environment. As increasing green awareness notably inspires emission reduction, intervening to influence consumer demand acts as an efficient way of achieving both profitability and sustainability.

The present research has many limitations and opportunities exist for further research. (1) This paper considers dual contracts, including the option and warehousing contracts, to coordinate the supply chain, while many other contracts can be discussed to achieve Pareto-efficient cooperation, like bilateral participation contracts. (2) This paper conducts research under the ETS, but there are other emission policies to reduce carbon pollution, like emission tax. It would be worthwhile to study the coordination problem with different contracts or with different emission policies. (3) This paper uses a basic supply chain with only one retailer and one manufacturer producing one kind of product during one period. However, research works would be conducted with different supply chain structures with multi-period coordination.

References:

Apple. Inc. (2020). Apple commits to be 100 percent carbon neutral for its supply chain and products by 2030 [Press release]. Retrieved from <https://www.apple.com/newsroom/2020/07/apple-commits-to-be-100-percent-carbon-neutral-for-its-supply-chain-and-products-by-2030/>

- Barratt, M. (2004). Understanding the meaning of collaboration in the supply chain. *Supply Chain Management*, 9(1), 30-42.
- Basiri, Z., & Heydari, J. (2017). A mathematical model for green supply chain coordination with substitutable products. *Journal of Cleaner Production*, 145, 232-249.
- Begen, M. A., Pun, H., & Yan, X. (2016). Supply and demand uncertainty reduction efforts and cost comparison. *International Journal of Production Economics*, 180, 125-134.
- Blome, C., Paulraj, A., & Schuetz, K. (2014). Supply chain collaboration and sustainability: a profile deviation analysis. *International Journal of Operations & Production Management*, 34(5), 639-663.
- Burton, E. S., & Sanjour, W. (1970). A simulation approach to air pollution abatement program planning. *Socio-Economic Planning Sciences*, 4(1), 147-159.
- Brécard, D. (2013). Environmental quality competition and taxation in the presence of green network effect among consumers. *Environmental & Resource Economics*, 54(1), 1-19.
- Cachon, G. P. (2003). Supply chain coordination with contracts. *Handbooks in Operations Research and Management Science*, 11, 227-339.
- Cai, J., Hu, X., Han, Y., Cheng, H., & Huang, W. (2016). Supply chain coordination with an option contract under vendor-managed inventory. *International Transactions in Operational Research*, 23(6), 1163-1183.
- Chen, F. Y., Hum, S. H., & Sun, J. (2001). Analysis of third-party warehousing contracts with commitments. *European Journal of Operational Research*, 131(3), 603-610.
- Chen, L., Zhao, X., Tang, O., Price, L., Zhang, S., & Zhu, W. (2017). Supply chain collaboration for sustainability: A literature review and future research agenda. *International Journal of Production Economics*, 194, 73-87.
- Chen, X., Hao, G., & Li, L. (2014). Channel coordination with a loss-averse retailer and option contracts. *International Journal of Production Economics*, 150, 52-57.
- Chitra, K. (2007). In search of the green consumers: a perceptual Study. *Journal of Services Research*, 7(1).
- Du, S., Hu, L., & Song, M. (2016). Production optimization considering environmental performance and preference in the cap-and-trade system. *Journal of Cleaner Production*, 112, 1600-1607.
- Du, S., Zhu, J., Jiao, H., & Ye, W. (2015). Game-theoretical analysis for supply chain with consumer preference to low carbon. *International Journal of Production Research*, 53(12), 3753-3768.
- He, L., Yuan, B., Bian, J., & Lai, K. K. (2023). Differential game theoretic analysis of the dynamic emission abatement in low-carbon supply chains. *Annals of Operations Research*, 324(1-2), 355-393.
- Hong, Z., & Guo, X. (2019). Green product supply chain contracts considering environmental responsibilities. *Omega*, 83, 155-166.
- Hu, L., Tang, W., Du, S., Wang, B., & Zhu, Y. (2022). The effects of leadership in Clean Development Mechanism low-carbon operations. *Transportation Research Part E: Logistics and Transportation Review*, 158, 102575.
- Huang, J., Xie, D., Qiu, Y., Wang, J., & Song, J. (2023). Green supply chain management: a renewable energy planning and dynamic inventory operations for perishable products. *International Journal of Production Research*, 1-28.
- Intergovernmental Panel on Climate Change. (2014). Climate change 2014: mitigation of climate change.
- Jadhav, A., Orr, S., & Malik, M. (2019). The role of supply chain orientation in achieving supply chain sustainability. *International Journal of Production Economics*, 217, 112-125.
- Giri, B., & Sarker, B. R. (2017). Improving performance by coordinating a supply chain with third party logistics outsourcing under production disruption. *Computers & Industrial Engineering*, 103, 168-177.
- Jeuland, A. P., & Shugan, S. M. (1983). Managing channel profits. *Marketing Science*, 2(3), 239-272.
- Ji, J., Zhang, Z., & Yang, L. (2017). Carbon emission reduction decisions in the retail-/dual-channel supply chain with consumers' preference. *Journal of Cleaner Production*, 141, 852-867.
- Koh, S. C. L., Jia, F., Gong, Y., Zheng, X., & Dolgui, A. (2023). Achieving carbon neutrality via supply chain management: position paper and editorial for IJPR special issue. *International Journal of Production Research*, 61(18), 6081-6092.
- Kumar, D., Singh, R. K., Mishra, R., & Vlachos, I. (2023). Big data analytics in supply chain decarbonisation: a systematic literature review and future research directions. *International Journal of Production Research*, 1-21.
- Lin, B., & Jia, Z. (2017). The impact of Emission Trading Scheme (ETS) and the choice of coverage industry in ETS: A case study in China. *Applied Energy*, 205, 1512-1527.
- Lin, B., & Jia, Z. (2019). What are the main factors affecting carbon price in Emission Trading Scheme? A case study in China. *Science of The Total Environment*, 654, 525-534.
- Liu, X., Xiong, R., Perera, S. C., & Guo, P. (2023). Collaborative management of the energy-water-carbon footprint: analysing the spatial network characteristics. *International Journal of Production Research*, 1-21.

- Liu, Z. L., Anderson, T. D., & Cruz, J. M. (2012). Consumer environmental awareness and competition in two-stage supply chains. *European Journal of Operational Research*, 218(3), 602-613.
- Luo, Z., Chen, X., & Wang, X. (2016). The role of coopetition in low carbon manufacturing. *European Journal of Operational Research*, 253(2), 392-403.
- Martin, R., Muûls, M., & Wagner, U. J. (2016). The impact of the European Union Emissions Trading Scheme on regulated firms: what is the evidence after ten years? *Review of environmental economics and policy*, 10(1), 129-148.
- Moon, W., Florkowski, W. J., Brückner, B., & Schonhof, I. (2002). Willingness to pay for environmental practices: implications for eco-labeling. *Land Economics*, 78(1), 88-102.
- Peng, C., Erhun, F., Hertzler, E. F., & Kempf, K. G. (2012). Capacity planning in the semiconductor industry: Dual-mode procurement with options. *Manufacturing & Service Operations Management*, 14(2), 170-185.
- Peng, Q., Wang, C., & Xu, L. (2020). Emission abatement and procurement strategies in a low-carbon supply chain with option contracts under stochastic demand. *Computers & Industrial Engineering*, 144, 106502.
- Petruzzi, N. C., & Dada, M. (1999). Pricing and the newsvendor problem: a review with extensions. *Operations Research*, 47, 183-194.
- Sana, S. S. (2020). Price competition between green and non green products under corporate social responsible firm. *Journal of Retailing and Consumer Services*, 55, 102118.
- Sana, S. S. (2022a). Sale through dual channel retailing system—A mathematical approach. *Sustainability Analytics and Modeling*, 2, 100008.
- Sana, S. S. (2022b). A structural mathematical model on two echelon supply chain system. *Annals of Operations Research*, 315(2), 1997-2025.
- Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, 16(15), 1699-1710.
- Smith, S., & Swierzbinski, J. (2007). Assessing the performance of the UK Emissions Trading Scheme. *Environmental & Resource Economics*, 37(1), 131-158.
- Tsao, Y.-C., Lee, P.-L., Chen, C.-H., & Liao, Z.-W. (2017). Sustainable newsvendor models under trade credit. *Journal of Cleaner Production*, 141, 1478-1491.
- Villoria-Sáez, P., Tam, V. W., del Río Merino, M., Arrebola, C. V., & Wang, X. (2016). Effectiveness of greenhouse-gas Emission Trading Schemes implementation: a review on legislations. *Journal of Cleaner Production*, 127, 49-58.
- Wang, S., & Choi, S. (2019). The Emission Ordering Strategy with Green Awareness under the Emission Trading System (ETS). Paper presented at the *ICORES 2019*, Prague, Czech Republic.
- Wang, S., & Choi, S. (2020a). Decision analysis for the emission-limited manufacturer with option contracts under demand uncertainty. *Journal of Cleaner Production*, 120712.
- Wang, S., & Choi, S. (2020b). Decision analysis with green awareness and demand uncertainties under the option-available ETS system. *Computers & Industrial Engineering*, 140, 106254.
- Wang, S., & Choi, S. (2020c). Pareto-efficient coordination of the contract-based MTO supply chain under flexible cap-and-trade emission constraint. *Journal of Cleaner Production*, 250.
- Wang, S., Wu, Z., & Yang, B. (2018). Decision and performance analysis of a price-setting manufacturer with options under a flexible-cap emission trading scheme (ETS). *Sustainability*, 10(10), 3681.
- Xu, X., He, P., Xu, H., & Zhang, Q. (2017). Supply chain coordination with green technology under cap-and-trade regulation. *International Journal of Production Economics*, 183(PB), 433-442.
- Yakita, A. (2009). Technology choice and environmental awareness in a trade and environment context. *Australian Economic Papers*, 48(3), 270-279.
- Yang, H., & Chen, W. (2018). Retailer-driven carbon emission abatement with consumer environmental awareness and carbon tax: Revenue-sharing versus cost-sharing. *Omega*, 78, 179-191.
- Yu, W., Wang, Y., Feng, W., Bao, L., & Han, R. (2022). Low carbon strategy analysis with two competing supply chain considering carbon taxation. *Computers & Industrial Engineering*, 169, 108203.

Data Availability Statement

Data available within the article or its supplementary materials.

