Research on Supply Chain Coordination of Green Production and Green Sales Investment Decisions Under Random Demand

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Abstract. The increasing consumption of resources and environmental pollution are be-coming more serious issues. To achieve the national strategic goal of "dual carbon," enterprises throughout the supply chain are facing severe challenges. This article addresses the joint decision-making regarding inventory and carbon emission reduction efforts in green supply chains involving efforts by manufacturers and retailers. Firstly, a centralized system model for the supply chain is established, demonstrating that demand variability negatively impacts the profit of the centralized system. Secondly, concerning a decentralized system in which both manufacturers and retailers are working on carbon emission reduction, it is shown that a buyback contract with shared costs can coordinate the supply chain. The optimal expected profits of manufacturers and retailers are directly proportional to the costs they bear for carbon emission reduction. Numerical examples validate the research findings obtained.

Keywords: Green Supply Chain, Carbon Emission Reduction Efforts, Demand Variability, Supply Chain Coordination.

1 INTRODUCTION

The increasing consumption of resources and environmental pollution are becoming more serious issues [1]. According to research from the United Nations Environment Programme, carbon emissions and the extensive consumption of natural resources are the main sources of environmental problems and global warming. Against this backdrop, industries such as automobile manufacturing and smartphone production face increased pressure to reduce carbon emissions. Not only do these industries generate significant carbon emissions during the manufacturing process, but their products also have environmental impacts during use. To minimize the adverse environmental effects of production, upstream companies in the supply chain can invest more in research and development to produce greener products. However, manufacturing green products comes with substantial R&D costs. Fortunately, an increasing number of consumers are prioritizing eco-friendly features and demonstrating a preference for low-carbon consumption [2], being willing to pay higher prices for environmentally friendly products

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[3][4]. This presents a crucial opportunity for producing green products. Therefore, establishing a green supply chain is essential, posing requirements and challenges for both upstream and downstream enterprises in the supply chain to collectively reduce emissions [5]. Therefore, examining the decision problems in a supply chain where manufacturers and retailers engage in carbon reduction under stochastic linear demand from a game perspective, and identifying contracts that can coordinate manufacturers and retailers towards a common goal of carbon reduction, is of significant practical importance.

In the literature on decision-making efforts in green supply chain carbon reduction, Raj et al. [6] believe that since most production activities are undertaken by upstream companies, manufacturers are better positioned to make green efforts to reduce the environmental impact of production. Yang Huixiao et al. [7] examined the carbon emission reduction decision-making problem for manufacturers under wholesale price and revenue-sharing contracts with stochastic demand.

Contrary to the aforementioned research, this article considers a scenario where enterprises in the supply chain collectively participate in reducing carbon emissions. This paper also considers the joint impact of market demand variability on the carbon reduction decisions of manufacturers and retailers, as well as on inventory decisions. The main contributions of this paper are: (i) extending the deterministic and exponential demand functions proposed by Du et al. [8] to present a stochastic and general supply chain where both manufacturers and retailers make carbon emission reduction efforts; (ii) demonstrating that a two-way cost-sharing buyback contract can coordinate the supply chain, showing that the profits of manufacturers and retailers are directly proportional to the costs they bear for carbon emission reductions, and validating the above results through numerical examples.

2 CENTRALIZED SYSTEM MODEL OF THE SUPPLY CHAIN

This section considers a two-tier green supply chain system consisting of a manufacturer and a retailer facing stochastic linear demand. In real supply chains, carbon emissions are generated by the manufacturer during processes such as procurement and production, while the retailer generates carbon emissions during processes like inventory management and delivery. The carbon emission reduction efforts of the manufacturer are denoted as τ_m, $\tau_m \geq 0$, and the carbon emission reduction efforts of the retailer during inventory and delivery processes are denoted as τ_r, $\tau_r \geq 0$.

Assuming the market demand function $D(\tau_m, \tau_r)$ is given by:

$$D(\tau_m,\tau_r)= a+\theta_m\tau_m+\theta_r\tau_r +X_\alpha,\ 0\leqslant\alpha\leqslant 1 \tag{1}$$

Here, a represents the initial market demand (a>0), τ_m and τ_r are the green production efforts of the manufacturer and the green sales efforts of the retailer, respectively. θ_m and θ_r represent consumers' green preference coefficients for the production and sales stages of the product, with both θ_m and θ_r being positive constant random factors. The random factor X in equation (1) represents the number of potential consumers in the market, defined in the interval $[\underline{\ell}, \overline{\ell}]$. X_α represents a mean-preserving transformation of the random variable X, such that $X_\alpha=\alpha X+(1-\alpha)\mu$, where $0\leqslant\alpha\leqslant1$, and μ is the mean of X. Here, α represents market demand variability, which increases with α.

In the face of the stochastic market demand in equation (1), when the sales cycle begins, the retailer orders the product at a price c, with order quantity q and no consideration for fixed ordering costs. If the order quantity exceeds the realized market demand, the retailer must dispose of the excess products at a unit salvage value v. The carbon emission reduction costs for the manufacturer and the retailer are respectively denoted as $\varphi_m(\tau_m)$ and $\varphi_r(\tau_r)$, where $\varphi_m(\tau_m)$ is a strictly increasing convex function of τ_m ($\varphi_m'(\tau_m)>0$, $\varphi_m''(\tau_m) > 0$) and $\varphi_r(\tau_r)$ is a strictly increasing convex function of τ_r ($\varphi_r'(\tau_r)>0$, $\varphi_r''(\tau_r) > 0$).

The objective of the centralized system of the supply chain is to determine the order quantity q and the carbon emission reduction levels τ_m、τ_r to maximize expected profit, given as:

$$\max_{q\geq0,\tau_m\geq0,\tau_r\geq0} \pi_c(q, \tau_m, \tau_r)=E[p\min(q,D(\tau_m, \tau_r))+v(q-D(\tau_m, \tau_r))^+-cq-\varphi_m(\tau_m)-\varphi_r(\tau_r)], \quad (2)$$

The following property 1 provides the optimal solution $(q^c, \tau_m{}^c,\tau_r{}^c)$ and the optimal expected profit $\pi_c(q^c, \tau_m{}^c,\tau_r{}^c)$of the centralized system of the supply chain.

Property 1. Considers a centralized supply chain system,

(i) If all assumptions hold, then the profit $\pi_c(q, \tau_m, \tau_r)$ of the supply chain centralized system in equation (2) is a joint concave function of (q, τ_m, τ_r), with the optimal solution $(q^c, \tau_m{}^c, \tau_r{}^c)$ existing and being unique. q^c、$\tau_m{}^c$ and $\tau_r{}^c$ are determined by the following three equations:

$$q^c = \alpha F_X^{-1}(\rho)+a+\theta_m\tau_m^c+\theta_r\tau_r^c+(1-\alpha)\mu, \quad (3)$$

$$\theta_m(p-c)-\varphi_m'(\tau_m^c)=0, \quad (4)$$

$$\theta_r(p-c)-\varphi_r'(\tau_r^c)=0, \quad (5)$$

where $\rho=(p-c)/(p-v)$, $0<\rho<1$.

(ii) The optimal profit $\pi_c(q^c, \tau_m{}^c, \tau_r{}^c)$ is given by:

$$\pi_c(q^c,\tau_m{}^c,\tau_r{}^c)=(p-c)\left(a+\theta_m\tau_m^c+\theta_r\tau_r^c+\alpha GL_X(\rho)/\rho+(1-\alpha)\mu\right)-\varphi_r(\tau_r^c)-\varphi_m(\tau_m^c), \quad (6)$$

where $GL_X(\rho)$ is called the Generalized Lorenz Transform of the random variable X, introduced by Shorrocks [9]. The expression for $GL_X(\rho)$ is given by:

$$GL_X(\rho)=\int_{\underline{\ell}}^{F_X^{-1}(\rho)}(\rho-F_X(x))dx+\rho\underline{\ell}, \ 0<\rho<1, \quad (7)$$

Proof: (i) $\pi_c(q, \tau_m, \tau_r)$ can be rewritten as:

$$\pi_c(q,\tau_m,\tau_r)=(p-c)q-\alpha(p-v)\int_{\underline{\ell}}^{A(q,\tau_m,\tau_r)}F_X(x)dx-\varphi_m(\tau_m)-\varphi_r(\tau_r), \quad (8)$$

where

$$A(q,\tau_m,\tau_r)=\frac{q-a-\theta_m\tau_m-\theta_r\tau_r-(1-\alpha)\mu}{\alpha}, \quad (9)$$

Given carbon reduction efforts τ_m and τ_r, taking first and second-order partial derivatives of equation (8) with respect to q yields:

$$\frac{\partial\pi_c(q,\tau_m,\tau_r)}{\partial q}=p-c-(p-v)F_X(A(q,\tau_m,\tau_r)), \quad (10)$$

$$\frac{\partial^2 \pi_c(q,\tau_m,\tau_r)}{\partial q^2} = -\frac{p-v}{\alpha} f_X\left(A(q,\tau_m,\tau_r)\right), \tag{11}$$

Given order quantity q and carbon reduction effort τ_r, taking first and second-order partial derivatives of equation (8) with respect to τ_m gives:

$$\frac{\partial \pi_c(q,\tau_m,\tau_r)}{\partial \tau_m} = \theta_m(p-v)F_X\left(A(q,\tau_m,\tau_r)\right) - \varphi_m^{'}(\tau_m), \tag{12}$$

$$\frac{\partial^2 \pi_c(q,\tau_m,\tau_r)}{\partial {\tau_m}^2} = -\frac{\theta_m^2}{\alpha}(p-v) f_X\left(A(q,\tau_m,\tau_r)\right) - \varphi_m^{''}(\tau_m), \tag{13}$$

Given order quantity q and carbon reduction effort τ_m, taking first and second-order partial derivatives of equation (8) with respect to τ_r gives:

$$\frac{\partial \pi_c(q,\tau_m,\tau_r)}{\partial \tau_r} = \theta_r(p-v)F_X\left(A(q,\tau_m,\tau_r)\right) - \varphi_r^{'}(\tau_r), \tag{14}$$

$$\frac{\partial^2 \pi_c(q,\tau_m,\tau_r)}{\partial {\tau_r}^2} = -\frac{\theta_r^2}{\alpha}(p-v) f_X\left(A(q,\tau_m,\tau_r)\right) - \varphi_r^{''}(\tau_r), \tag{15}$$

Taking second-order partial derivatives of equation (8) with respect to q and τ_m gives:

$$\frac{\partial^2 \pi_c(q,\tau_m,\tau_r)}{\partial q \partial \tau_m} = \frac{1}{\alpha}\theta_m(p-v) f_X\left(A(q,\tau_m,\tau_r)\right), \tag{16}$$

Taking second-order partial derivatives of equation (8) with respect to q and τ_r gives:

$$\frac{\partial^2 \pi_c(q,\tau_m,\tau_r)}{\partial q \partial \tau_r} = \frac{1}{\alpha}\theta_r(p-v) f_X\left(A(q,\tau_m,\tau_r)\right), \tag{17}$$

Taking second-order partial derivatives of equation (8) with respect to τ_m and τ_r gives:

$$\frac{\partial^2 \pi_c(q,\tau_m,\tau_r)}{\partial \tau_m \partial \tau_r} = -\frac{1}{\alpha}\theta_m\theta_r(p-v) f_X\left(A(q,\tau_m,\tau_r)\right), \tag{18}$$

Upon computation, when all assumptions are met, the Hessian matrix is negative definite. $\pi_c(q, \tau_m, \tau_r)$ is a joint concave function of (q, τ_m, τ_r), and there exists a unique optimal solution$(q^c, {\tau_m}^c, {\tau_r}^c)$ that maximizes the expected profit of the centralized supply chain system. By solving for $\frac{\partial \pi_c(q,\tau_m,\tau_r)}{\partial q} = 0$、$\frac{\partial \pi_c(q,\tau_m,\tau_r)}{\partial \tau_m} = 0$ and $\frac{\partial \pi_c(q,\tau_m,\tau_r)}{\partial \tau_r} = 0$ in equations (10), (12), and (14), the optimal solutions for equations (3), (4), and (5) can be obtained, thereby proving Property 1(i).

(ii) Substituting the optimal solution $(q^c, {\tau_m}^c, {\tau_r}^c)$ from equations (3), (4), and (5) into equation (8) , the optimal profit of the centralized supply chain system is obtained, thus proving Property 1(ii).

3 ANALYSIS OF SUPPLY CHAIN COORDINATION CONTRACTS

In this article, we consider a repurchase plus two-way cost-sharing contract model $\{w,b,\lambda_m,\lambda_r\}$. The manufacturer offers a repurchase plus two-way cost-sharing contract to the retailer, bearing the risk of the retailer ordering more products. Through two-way cost-sharing, the manufacturer partially covers the cost of the retailer's carbon reduction efforts, while the retailer partially covers the cost of the manufacturer's carbon reduction efforts. The transfer payment between the retailer and the manufacturer is defined as:

$$T(q)= wq-(b-v)(q-D(\tau_m,\tau_r))^{+}+(1-\lambda_m)\varphi_m(\tau_m)-(1-\lambda_r)\varphi_r(\tau_r), \tag{19}$$

where the manufacturer decides the wholesale price w and the carbon reduction effort level τ_m, and the retailer determines the order quantity q and the carbon reduction effort level τ_r. The manufacturer shares the cost of the retailer's carbon reduction efforts at a rate of$(1-\lambda_r)$, while the retailer shares the cost of the manufacturer's carbon reduction efforts at a rate of $(1-\lambda_m)$.

The manufacturer's objective is to determine the optimal carbon reduction effort level τ_m to maximize their expected profit, defined as:

$$\max_{\tau_m\geq 0} \pi_m(q,\tau_m,\tau_r)= E[\Pi_m(q, D(\tau_m,\tau_r))], \tag{20}$$

where

$$\Pi_m(q, D(\tau_m,\tau_r))=(w-c)q-(b-v)(q-D(\tau_m,\tau_r))^{+}-\lambda_m\varphi_m(\tau_m)-(1-\lambda_r)\varphi_r(\tau_r), \tag{21}$$

and the retailer aims to decide on the order quantity q and the carbon reduction effort level τ_r to maximize their expected profit, defined as:

$$\max_{q\geq 0,\tau_r\geq 0} \pi_r(q,\tau_m,\tau_r)=E[\Pi_r(q, D(\tau_m,\tau_r))], \tag{22}$$

where

$$\Pi_r(q, D(\tau_m,\tau_r))=(p-w)q-(p-b)(q-D(\tau_m,\tau_r))^{+}-\lambda_r\varphi_r(\tau_r)-(1-\lambda_m)\varphi_m(\tau_m). \tag{23}$$

Property 2. Consider a decentralized supply chain system under a buyback with dual-channel cost-sharing contract. The following hold:

(i) Under the provided assumptions, the manufacturer's profit function is strictly concave in τ_m, with a unique optimal solution τ_m^*; and the retailer's profit function is jointly concave in (q, τ_r), yielding a unique joint optimal solution (q^*, τ_r^*).

(ii) The decentralized system's optimal solution (q^*,τ_m^*,τ_r^*) exists, q^*、τ_m^* and τ_r^* are determined by the following three equations:

$$q^* = \alpha F_X^{-1}\left(\rho^\lambda\right)+a+\theta_m\tau_m^*+\theta_r\tau_r^*+(1-\alpha)\mu, \tag{24}$$

$$\theta_m\rho^\lambda(b-v)\big|-\lambda_m\varphi_r'\left(\tau_m^*\right)=0, \tag{25}$$

$$\theta_r\left(p-w\right)-\lambda_r\varphi_r'\left(\tau_r^*\right)=0, \tag{26}$$

Where $\rho^\lambda=(p-w)/(p-b)$。

(iii) The manufacturer's optimal profit is given by

$$\pi_m\left(q^*,\tau_m^*,\tau_r^*\right)=(w-c)q^*-\alpha(b-v)\int_{\underline{\ell}}^{F_X^{-1}(\rho^\lambda)}F_X(x)\,dx-\lambda_m\varphi_m\left(\tau_m^*\right)-(1-\lambda_r)\varphi_r\left(\tau_r^*\right), \tag{27}$$

Where $\rho^\lambda=(p-w)/(p-b)$。

(iv) The retailer's optimal profit is given by

$$\pi_r\left(q^*,\tau_m^*,\tau_r^*\right)=(p-w)\left[a+\theta_m\tau_m^*+\theta_r\tau_r^*+\alpha F_X^{-1}\left(\rho^\lambda\right)/\rho^\lambda+(1-\alpha)\mu\right]-\lambda_r\varphi_r\left(\tau_r^*\right)-(1-\lambda_m)\varphi_m\left(\tau_m^*\right), \tag{28}$$

where $\rho^\lambda=(p-w)/(p-b)$, and $GL_X(\rho)$ is derived from Equation (7).

Theorem 1. Considers a decentralized supply chain system:

(i) Repurchase with two-way cost-sharing contracts $\{w,b,\lambda_m,\lambda_r\}$ can coordinate supply chains dependent on green production and green sales efforts only when w^*、b^*、λ_m^* and λ_r^* satisfy:

$$w^*=p-(1-\lambda_m^*)(p-c), \tag{29}$$

$$b^*=p-(1-\lambda_m^*)(p-v), \tag{30}$$

$$\lambda_m^{*}+\lambda_r^{*}=1, \tag{31}$$

(ii) When Theorem 1(i) is satisfied, the optimized profits for the retailer and manufacturer post-coordination are represented as:

$$\pi_m(q^{*},\tau_m^{*},\tau_r^{*})=\lambda_m^{*}\pi_c(q^c,\tau_m^c,\tau_r^c), \tag{32}$$

$$\pi_r(q^{*},\tau_m^{*},\tau_r^{*})=\lambda_r^{*}\pi_c(q^c,\tau_m^c,\tau_r^c), \tag{33}$$

where $\lambda_r^{*}+\lambda_m^{*}=1$, and $\pi_c(q^c, \tau_m^c,\tau_r^c)$ is given by Eq. (6).

Proof: (i) Based on Cachon [10] definition of supply chain coordination, the optimal order quantity for the retailer, the optimal green sales effort for the retailer, and the optimal green production effort for the manufacturer should all align with the optimal decisions of a centralized system. By comparing Eqs. (3) and (24), Eqs. (4) and (25), as well as Eqs. (5) and (26), the following relationships can be derived:

$$(p-w)/(p-b)=(p-c)/(p-v), \tag{34}$$

$$(p-b)/\lambda_r=p-v, \tag{35}$$

$$(b-v)/\lambda_m=p-v, \tag{36}$$

By simultaneous equations (34), (35), and (36), $b^{*}= p-(1-\lambda_m^{*})(p-v)$ and $w^{*}= p-(1-\lambda_m^{*})(p-c)$, $\lambda_r^{*}+\lambda_m^{*}=1$, Theorem 1(i) is thus proven.

(ii) Substituting Eqs. (29), (30), and (31) into Eqs. (27) and (28) respectively, Theorem 1(ii) can be established.

4 NUMERICAL EXAMPLES

Example 1. Assuming p=10, v=2, a=3, θ_m=0.6, θ_r=0.4 and c taking values of 4 and 8, representing inventory service levels of 0.75 and 0.25 respectively, where ρ=0.75 denotes high-profit products and ρ=0.25 denotes low-profit products. Assuming the random variable X follows a uniform distribution defined on the interval [-1, 1], with a mean of 0. Assuming $\varphi_m(\tau)=k_m\tau_m^2/2$, $\varphi_r(\tau)=k_r\tau_r^2/2$, k_m=0.5, k_r=0.4. Table 1 illustrates the impact of demand variability on supply chain centralized system.

Table 1. Optimal decisions and profits of the supply chain centralized system under different values of α.

α	ρ=0.75				ρ=0.25			
	q^c	τ_m^c	τ_r^c	$\pi_c(q^c, \tau_m^c, \tau_r^c)$	q^c	τ_m^c	τ_r^c	$\pi_c(q^c, \tau_m^c, \tau_r^c)$
0.10	9.77	7.2	6.0	38.01	5.19	2.4	2.0	7.99
0.30	9.87	7.2	6.0	37.71	5.09	2.4	2.0	7.49
0.50	9.97	7.2	6.0	37.41	4.99	2.4	2.0	6.99
0.70	10.07	7.2	6.0	37.11	4.89	2.4	2.0	6.49
0.90	10.17	7.2	6.0	36.81	4.79	2.4	2.0	5.99

Table 1 verifies the relevant properties under the supply chain centralized system. α represents demand variability, where with increasing demand variability, the optimal order quantity for high-profit products gradually increases while for low-profit products, it decreases. Both high-profit and low-profit products in the supply chain centralized system show a decrease in optimal profits with increasing demand variability, implying that reducing demand variability is beneficial for the overall supply chain.

5 CONCLUSION

This paper extends the deterministic and exponential demand functions proposed by Du et al. [8] to present a stochastic and general supply chain where both manufacturers and retailers make carbon emission reduction efforts. The study concludes: (i) In a centralized system, the optimal profit of the supply chain centralized system decreases with increasing demand variability, indicating adverse effects of demand variability on supply chain profits. (ii) In a decentralized supply chain system, it is demonstrated that the repurchase plus bidirectional cost-sharing contract can coordinate the supply chain. The optimal profits of manufacturers and retailers are directly proportional to the green investment costs they share. Further research areas could include: (i) How do the optimal decisions and profits of the supply chain change when considering the dynamic model of decentralized supply chain systems? (ii) How does retailer risk preference affect the optimal decisions and utility of the supply chain system?

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