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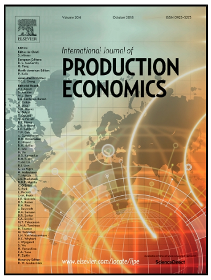

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Green Supply Chain Management under Capital Constraint

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Green Supply Chain Management under Capital Constraint

Abstract

To determine how carbon emissions reduction affects supply chain operations and financing decisions, this paper examines a green supply chain, which consists of one manufacturer (playing the leading role) and one capital-constrained retailer; in this supply chain, bank financing and trade credit financing are viable. This research explores the retailer's optimal order quantity, the manufacturer's optimal wholesale price, the optimal level of carbon emissions (for both bank financing and trade credit financing), and the design of the contract to coordinate the supply chain. We find that the supply chain achieves a win-win outcome in terms of production quantity and emissions reduction when the manufacturer invests in emissions reduction. In addition, we find that a supply chain with a contract outperforms a non-contract supply chain in production quantity and emissions reduction. Furthermore, the effect is more remarkable when trade credit financing is viable.tra

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Green Supply Chain Management under Capital Constraint

Introduction

The costly effects of global warming are continuously increasing and impacting economies all over the world. One of the main causes of global warming is the greenhouse effect, which is triggered by the increase of carbon dioxide emissions into the atmosphere (Gleick et al., 2010). To solve this problem, almost 200 countries committed to participating in the Paris Agreement in 2015. This agreement aimed to control and mitigate the negative effects of climate change (such as the world's rising average temperature and greenhouse gas emissions). Due to an increasing recognition of the importance of environmental protection, there is currently a trend of attempts to address the issue of pollution caused by industrial development within the supply chain management process. Recent research has discussed this trend under the term "green supply chain management" and has introduced the concepts of sustainability and environmental thinking to green supply chain management (Sheu et al., 2005). Green supply chain management incentivizes manufacturers and retailers to take emission reduction into consideration when making business decisions. Researchers have found that green supply chain management is a win-win strategy for both retailers and manufacturers. Zhao et al. (2012) discovered that economic profits can be enhanced by improving a company's environmental performance (from production to sales). Ma and Gao (2013) suggested that, by determining the wholesale price together, the supply chain can make more returns by reducing carbon emissions. Chen et al. (2013) claimed

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that a supply chain can reduce its carbon emissions without increasing costs; this can be done by changing the order quantity of the product.

In this context, our paper examined a supply chain consisting of one manufacturer (playing the leading role) and one capital-constrained retailer. In this scenario, the manufacturer takes measures to reduce carbon emissions, while the retailer is capital constrained and financed by a bank or the manufacturer. This paper is organized as follows: The Literature Review section addresses relevant research on the topic of green supply chain management and explains how this work will contribute to the existing literature. The types of supply chains and settings that are used in this research are illustrated in the Model section. Two ways of financing and decision making to determine wholesale prices, order quantities, and levels of carbon emissions are discussed in the Bank Finance and Trade Credit Financing sections. A simplified example illustrates how the retailer's financing and capital can influence the order quantity and the reduction of carbon emissions. The findings are presented in the Conclusion section.

Literature Review

Many researchers have investigated the optimal strategy for carbon emission reduction (from production to sales); the most relevant metrics include the wholesale price and order quantity. Song and Leng (2012) examined supply chain strategies in terms of three kinds of policies: the mandatory carbon emissions cap, trade policies, and taxing policies. Zhang et al. (2011) investigated the manufacturer's production

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model under single or multiple carbon purification with random demand. Jaber et al. (2013) proposed that carbon emissions are a function of the production level and that companies should be punished if their carbon emissions exceed the mandatory cap; however, companies can raise their cap by buying carbon emission rights. Liang and Xiong (2014) studied the Stackelberg model with a single manufacturer playing the leading role and with single retailers. In their model, demand within the market was influenced by the level of carbon emissions reduction. Benjaafar et al. (2013) used the economic order quantity model to argue that companies profit when they cooperate with others or not and when the government introduces different policies (such as a carbon emission caps, trade, taxation, or compensation). Du et al. (2013) utilized game theory to examine how, in a classical newsvendor model, manufacturers (who have carbon emission rights) and retailers negotiate conditions of buying and selling carbon emission rights. Letmathe and Balakrishnan (2005) used two models to discuss companies' production quantity under different environmental constraints. Hoen et al. (2014) discussed the optimal carbon emission reduction for two selectable logistic models. Rosič and Jammernegg (2013) examined a retailer's optimal order quantity within the green supply chain if the retailer has both offshore and onshore suppliers.

Previous research has explored how manufacturers and retailers can make optimal decisions in terms of their different carbon sources, policies, costs of carbon emissions, and supply chain models. However, the previous research has not taken retailers' capital constraints into consideration. However, if the retailer gets financing from the bank or a manufacturer, the retailer will go bankrupt when the demand of the market is very

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low. Therefore, we contributed to the previous research by investigating a green supply chain under the capital constraints of the retailer.

Model

The model investigated a supply chain that includes one manufacturer (who plays the leading role) and one capital-constrained retailer, for whom bank financing and trade credit financing are viable. Without taking carbon emissions and reduction policies into consideration, the product market's demand D is random. Assuming that the distribution function $F(D)$ is continuously differentiable and that the general failure rate $H(D) = D\frac{f(D)}{\bar{F}(D)}$, with a hazard rate $h(D) = \frac{f(D)}{\bar{F}(D)}$, $H(D)$ and $h(D)$ are increasing in D (Jing et al., 2012; Kouvelis and Zhao, 2015).

Considering that customers prefer green products, we assumed that reducing emissions will expand the market size. The higher the carbon emission reductions, the more products the customer will want to buy. Here, we used $g(e)$ to represent the increased demand caused by making efforts to reduce carbon emissions. For $g(e) = b$ e, $b > 0$ is a constant, and e represents the level of carbon emissions reduction. After making efforts to reduce carbon emissions, the market demand becomes $D + g(e)$; the corresponding cost is $\frac{1}{2}ae^2$, where a is a constant, which is called the carbon emission cost parameter (Giri et al., 2013). In this research, we assumed that the manufacturer bears $\frac{1}{2}\theta ae^2$ and the retailer bears $\frac{1}{2}(1-\theta)ae^2$ of the cost of reducing carbon emissions.

A single-period product market was considered in this market. In this marketing period, the retailer orders q units of the product at a wholesale price w and sells the product at another price p. The manufacturer and retailer do not have costs other than the manufacturer's unit production cost c, with $c < w < p$. The retailer has working capital B, with $B < wq$, so the retailer is capital constrained and needs to get financing from a bank or the manufacturer. At the end of the marketing period, the retailer needs to repay $(wq - B)(1 + r)$ to the bank or the manufacturer at an interest rate r. In this model, the product has zero salvage value, and we ignored the goodwill lost, which is generated by an unsatisfied market demand. In addition, the manufacturer and retailer are risk-neutral, and all the information, such as the retailer's capital B, can be observed by the manufacturer, retailer, and bank.

Bank Financing

In this section, we show how retailers and manufacturers make decisions to maximize their profits in a decentralized supply chain under the condition of bank financing. At the beginning of the marketing period, the retailer orders q products at a wholesale price w. Due to the retailer's capital $B < wq$, the retailer needs to borrow $(wq - B)$ from the bank and pay wq to the manufacturer for the product. If the market demand $D + g(e)$ during the marketing period does not exceed the retailer's order quantity q, then the retailer can only sell $D + g(e)$ products during this period. Alternatively, if the market demand $D + g(e)$ exceeds the retailer's order quantity q, the retailer can sell q products. Therefore, the retailer's revenue is $p\min\{(D + g(e)),q\}$. At the end of this period, the retailer needs to repay $(wq - B)(1 + r)$ to the bank, where r is the interest rate charged by the bank. When the demand of the market is very low, the retailer's revenue p

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$(D + g(e))$ is smaller than $(wq - B)(1 + r)$; in such cases, the retailer can only repay $p(D + g(e))$, and the retailer will go bankrupt. As a result, the bank will suffer a loss $[(wq - B)(1 + r) - p(D + g(e))]$. We used $q_{0,B}$ to represent the market demand threshold when the retailer goes bankrupt, which is given by the following:

$$q_{0,B} = \frac{(wq - B)(1 + r)}{p}. \tag{1}$$

To consider the possible loss when the bank lends to the retailer, the expected profit should be equal to the average investment return on the capital market. Here, we used r_f to represent the rate of the average investment return; in a fully competitive bank market, the rate is $r_f = 0$. As a result, the bank will use the following equation to design the interest rate:

$$\int_0^{q_{0,B} - g(e)} p(D + g(e)) f(D) dD + \int_{q_{0,B} - g(e)}^{\infty} q_{0,B} p f(D) dD = (wq - B)\left(1 + r_f\right). \tag{2}$$

It can be simplified as follows:

$$\frac{q_{0,B}\left(1 + r_f\right)}{(1 + r)} = \int_0^{q_{0,B} - g(e)} (D + g(e)) f(D) dD + q_{0,B} \int_{q_{0,B} - g(e)}^{\infty} f(D) dD. \tag{3}$$

The retailer's problem

Ahead of the marketing period, the capital-constrained retailer pays the manufacturer wq, which consists of the retailer's capital B and the bank's financing $(wq - B)$. At the end of this period, the retailer's revenue is $pmin[D + g(e),q]$, and the retailer repays $min[pmin[D + g(e),q],(wq - B)(1 + r)]$ to the bank. Thus, the retailer needs to choose the optimal order quantity to maximize his or her profit. His or her expected profit is as follows:

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$$\begin{aligned}\pi_{r,B} &= \int_{q_{0,B}-g(e)}^{q-g(e)} p\left(D+g\left(e\right)\right) f\left(D\right) dD + \int_{q-g(e)}^{\infty} pqf\left(D\right) dD \\ &- \int_{q_{0,B}-g(e)}^{\infty} \left(wq-B\right)\left(1+r\right) f\left(D\right) dD - B - \frac{1}{2}\left(1-\theta\right) ae^2\end{aligned} \quad . \tag{4}$$

Plugging Equation (3) into Equation (4) results in the following:

$$\pi_{r,B} = p_r\left[q - \int_0^{q-g(e)} F\left(D\right) dD\right] - wq\left(1+r_f\right) + Br_f - \frac{1}{2}\left(1-\theta\right) ae^2 . \tag{5}$$

Proposition 1. *In a decentralized supply chain where the capital-constrained retailer gets financing from a bank (for the given wholesale price w and level of carbon emission reduction e), the retailer's optimal order quantity ${q_B}^*$ satisfies the first-order optimality condition of its expected profit function. This is given as follows:*

$$q_r = \overline{F}^{-1}\left(\frac{w\left(1+r_f\right)}{p_r}\right) + g\left(e\right). \tag{6}$$

From Equation (6) $\frac{dq}{de} = g'(e) = b$, there is a positive correlation between the retailer's optimal order quantity and the level of carbon emissions reduction. This means that the more efforts that are taken to reduce carbon emissions, the more products the retailer will order.

The manufacturer's problem

At time zero of the selling period, the manufacturer sells q units of the product to the retailer at a wholesale price w. Since the manufacturer's profit is a function of (w, q, e) and q is the function of w, the manufacturer needs to choose the optimal wholesale price w and the optimal level of carbon emissions reduction e to maximize their profits. Thus, when the retailer gets financing from a bank, the manufacturer's profit function is expressed as follows:

$$\pi_{m,B} = \left(w-c\right) q - \frac{1}{2}\theta ae^2 . \tag{7}$$

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Proposition 2. *In a decentralized supply chain, in which the capital-constrained retailer receives bank financing, the manufacturer's optimal wholesale price and optimal level of carbon emissions reduction* $\left(w_B{}^*, e_B{}^*\right)$ *are uniquely given by the following:*

$$\bar{F}^{-1}\left(\frac{w\left(1+r_f\right)}{p_r}\right)+g\left(e\right)-\frac{\left(w-c\right)\left(1+r_f\right)}{pf\left(\frac{w\left(1+r_f\right)}{p_r}\right)}=0. \tag{8}$$

$$e=\frac{\left(w-c\right)g'\left(e\right)}{\theta a}. \tag{9}$$

Equation (9) shows that the relation between the manufacturer's optimal levels of carbon emissions reduction and wholesale price is positive; however, the relations between the manufacturer's optimal level of carbon emissions reduction and production costs, carbon emission cost parameters, and cost sharing coefficients of reducing carbon emissions are negative.

Trade Credit Financing

In this section, we show how the retailer and manufacturer can make decisions to maximize their profits in a decentralized supply chain if the retailer receives trade credit financing. Since the retailer's capital is $B < wq$, the manufacturer agrees that the retailer only pays B at time zero. However, the manufacturer requires the retailer to repay the lent money with interest at the end of this period. Since the manufacturer can gain interest by charging a higher wholesale price, we assumed the interest rate to be zero, which means the retailer will need to repay $(wq - B)$ at the end of the period. The same is applied to the condition of bank financing; when the demand of the market is very low, the retailer's revenue $p(D+g(e))$ will not exceed $(wq-B)$. The retailer will only be able to repay $p(D+g(e))$ to the manufacturer, causing the retailer to go bankrupt and the manufacturer to suffer a loss of $[(wq-B)-p(D+g(e))]$. We used $q_{0,T}$ to represent the market demand when the retailer goes bankrupt; $q_{0,T}$ is given by the following:

$$q_{0,T}=\frac{(wq-B)}{p}. \tag{10}$$

The retailer's problem

At time zero of the selling period, the capital-constrained retailer pays B to the manufacturer. At the end of this period, the retailer's revenue is $pmin[D+g(e),q]$, which requires him or her to repay $min[pmin[D+g(e),q],(wq-B)]$ to the manufacturer. Thus, the retailer needs to choose the optimal order quantity to maximize his or her profit; his or her expected profit is expressed as follows:

$$\pi_{r,T}=(p-w)q-\int_{q_{0,T}-g(e)}^{q-g(e)}pF(D)dD-\frac{1}{2}(1-\theta)ae^2. \tag{11}$$

Proposition 3. *In a decentralized supply chain where the capital-constrained retailer receives trade credit financing (for the given wholesale price w and level of carbon emissions reduction e), the retailer's optimal order quantity ${q_T}^*$ satisfies the first-order optimality condition of its expected profit function, which is uniquely given as follows:*

$$p\overline{F}(q-g(e))=w\overline{F}(q_{0,T}-g(e)),\ \ where\ \ q_{0,\mathrm{T}}=\frac{(wq-B)}{p}. \tag{12}$$

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The manufacturer's problem

As was mentioned earlier, we assumed that the market information can be observed perfectly; so, when the manufacturer publishes the wholesale price w, the manufacturer will know the retailer's order quantity q. Thus, the manufacturer will maximize their expected profit by choosing the optimal wholesale price w. Under this condition, the manufacturer's expected profit function is as follows:

$$\pi_{m,T} = (w-c)q - \int_0^{q_{0,T}-g(e)} pF(D)\,dD - \frac{1}{2}\theta a e^2. \tag{13}$$

Proposition 4. *In a decentralized supply chain where the capital-constrained retailer receives trade credit financing, the manufacturer's optimal profit wholesale price and level of carbon emission reduction* $\left(w_T{}^*, e_T{}^*\right)$ *are uniquely given by the following:*

$$\frac{p\bar{F}\big(q-g(e)\big)\big[1-qh\big(q-g(e)\big)\big]}{1-\frac{wq}{p}h\big(q_{0,T}-g(e)\big)} - c = 0. \tag{14}$$

$$e = \left[\frac{\left(p^2-\frac{p^3}{w}\right)\bar{F}\big(q-g(e)\big)+c\left(w-\frac{w^2}{p}\right)f\big(q_{0,T}-g(e)\big)}{\left[pf\big(q-g(e)\big)-\frac{w^2}{p}f\big(q_{0,T}-g(e)\big)\right]} + p - c\right]\frac{g'(e)}{\theta a}. \tag{15}$$

where $q_{0,\mathrm{T}} = \dfrac{(wq-B)}{p}$ and $p\bar{F}\big(q-g(e)\big) = w\bar{F}\big(q_{0,T}-g(e)\big)$.

Supply Chain Contract

This section shows how the contract between the manufacturer and the retailer can be designed to coordinate the supply chain. At the beginning of the selling period, the manufacturer and retailer negotiate the contract (w,α,θ,T), where w is the wholesale price, α is the revenue share of the retailer, and θ is the carbon emission reduction cost

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share of the manufacturer. T is the amount of money that the manufacturer agrees to transfer to the retailer at the end of this selling period, which is a fixed amount. It is important to know that, in this contract, payments between supply chain parties have priority over bankruptcy proceedings (Kouvelis and Zhao, 2015).

A supply chain contract of bank financing

After the contract is designed, the retailer orders q products at a wholesale price w. Since the retailer's capital is $B < wq$, the retailer needs to borrow $(wq - B)$ from the bank and pay wq to the manufacturer for the product. If the market demand $D + g(e)$ during the marketing period does not exceed the retailer's order quantity q, then the retailer can sell only $D + g(e)$ units of the product during this period. Alternatively, if the market demand $D + g(e)$ exceeds the retailer's order quantity q, the retailer can sell q units of the product. At the end of the selling period, the retailer shares $(1 - \alpha)$ revenue with manufacturer, and the manufacturer gives T amount of money to the retailer. Therefore, the retailer's revenue is $\alpha p \min\{(D + g(e)), q\} + T$. However, the retailer still needs to repay $(wq - B)(1 + r)$ to the bank (where r is the interest rate charged by the bank). When the demand within the market is very low, the retailer's revenue $\alpha p(D + g(e)) + T$ will be smaller than $(wq - B)(1 + r)$; in such cases, the retailer can only repay $\alpha p(D + g(e)) + T$ and will go bankrupt. As a result, the bank will suffer a loss $[(wq - B)(1 + r) - \alpha p(D + g(e)) - T]$. We used $q_{0,B,C}$ to represent the market demand threshold when the retailer goes bankrupt, which is given by the following:

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$$q_{0,B,C} = \frac{(wq-B)(1+r)-T}{\alpha p}. \tag{16}$$

Considering the possibility of loss when the bank lends to the retailer, its expected profit should be equal to the average investment return on the capital market. Thus, we used r_f to represent the rate of the average investment return; in a fully competitive bank market, $r_f = 0$. Hence, the bank can use the following equation to determine an interest rate:

$$\alpha\left[\int_0^{q_{0,B,C}-g(e)} p\left(D+g(e)\right)f(D)\,dD + \int_{q_{0,B,C}-g(e)}^{\infty} pq_{0,B,C} f(D)\,dD\right] + T = (wq-B)\left(1+r_f\right) \tag{17}$$

The retailer's problem

At time zero of the marketing period, the capital-constrained retailer pays the manufacturer wq, which consists of the retailer's capital B and the bank's financing $(wq - B)$. At the end of this period, the retailer's revenue is $\alpha p min[D + g(e),q] + T$, and the retailer is required to repay $min[\alpha p min[D + g(e),q] + T,(wq - B)(1 + r)]$ to the bank. Thus, the retailer needs to choose the optimal order quantity to maximize his or her profit. His or her expected profit can be expressed as follows:

$$\begin{aligned}\pi_{r,B,C} &= \alpha\left[\int_{q_{0,B,C}-g(e)}^{q-g(e)} p\left(D+g(e)\right)f(D)\,dD + \int_{q-g(e)}^{\infty} pq_{0,B,C} f(D)\,dD\right] \\ &-\int_{q_{0,B,C}-g(e)}^{\infty}\left[(wq-B)(1+r)-T\right]f(D)\,dD - B - \frac{1}{2}(1-\theta)ae^2\end{aligned}. \tag{18}$$

Combining Equations (16) and (17) with Equation (18) produces the following:

$$\pi_{r,B,C} = \alpha p\left[q - \int_0^{q-g(e)} F(D)\,dD\right] - wq\left(1+r_f\right) + T + Br_f - \frac{1}{2}(1-\theta)ae^2. \tag{19}$$

Proposition 5. *With the designed contract (w,α,θ,T) in a decentralized supply chain* *where the capital-constrained retailer receives bank financing (for the given wholesale price* w *and level of carbon emissions reduction* e*), the retailer's optimal order quantity* ${q_{B,C}}^*$ *satisfies the first-order optimality condition of its expected profit function, which is given as follows:*

$$q = \overline{F}^{-1}\left(\frac{w\left(1+r_f\right)}{\alpha p}\right) + g\left(e\right). \tag{20}$$

The manufacturer's problem

At time zero of the selling period, the manufacturer sells q units of the product to the retailer at a wholesale price of w. Since the manufacturer's profit is a function of (w, q, e) and q is the function of w, the manufacturer needs to choose the optimal wholesale price w and level of carbon emissions reduction e to maximize their profits. Thus, when the retailer receives financing from the bank, the manufacturer's profit function is as follows:

$$\pi_{m,B,C} = \left(1-\alpha\right) p\left[q - \int_0^{q-g(e)} F\left(D\right) dD\right] + \left(w-c\right) q - T - \frac{1}{2}\theta a e^2 . \tag{21}$$

Supply chain coordination contract

When taking the supply chain as a centralized system, the manufacturer and retailer will work together to coordinate the supply chain. Under this condition, the supply chain's profit $\pi_{s,B,C}$ is equal to the manufacturer's profit plus the retailer's profit, which is expressed as follows:

$$\pi_{s,B,C} = \pi_{r,B,C} + \pi_{m,B,C} = p\left[q - q\int_0^{q-g(e)} F\left(D\right) dD\right] - cq - \left(wq - B\right) r_f - \frac{1}{2} a e^2 . \tag{22}$$

Proposition 6. *In a decentralized supply chain where the capital-constrained retailer* *receives bank financing, coordination can be achieved by designing the contract as* $(w_B, \alpha_B, \theta_B, T_B)$*, which is given by the following:*

$$w = \frac{\alpha c}{1 + r_f - \alpha r_f}, \tag{23}$$

$$\theta = 1 - \alpha . \tag{24}$$

The decentralized supply chain's optimal order quantity and optimal level of carbon emissions reduction $\left(q_{B,C}{}^{*}, e_{B,C}{}^{*}\right)$ *are given by the following:*

$$q = \bar{F}^{-1}\left(\frac{c + wr_f}{p}\right) + g(e), \tag{25}$$

$$e = \left[p - c - wr_f\right]\frac{g'(e)}{\theta a}. \tag{26}$$

Comparing Equations (25) and (26) with Equations (6) and (9), we can obtain $q_{B,C}{}^{*} > q_B{}^{*}$ and $e_{B,C}{}^{*} > e_B{}^{*}$, showing that the supply chain with a contract outperforms the non-contract supply chain in terms of production quantity and emissions reduction (when bank financing is viable).

The supply chain contract of trade credit financing

After the contract is designed, since the retailer's capital is $B < wq$, the manufacturer agrees that the retailer only has to pay B at time zero but requires the retailer to repay the rest of the money with interest at the end of the period. Since the manufacturer can gain interest by charging a higher wholesale price, we assumed the interest rate to be zero, which means that the retailer needs to repay $(wq - B - T)$ at the end of the selling period. The same applies under the condition of bank financing; when the demand of the market is very low, the retailer's revenue $\alpha p(D + g(e)) + T$ does not exceed

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$(wq - B)$. Thus, the retailer can only repay $\alpha p(D + g(e)) + T$ to the manufacturer. As a result, the retailer goes bankrupt, and the manufacturer suffers a loss $[(wq - B) - \alpha p(D + g(e)) - T]$. We used $q_{0,T,C}$ to represent the market demand when the retailer goes bankrupt; $q_{0,T,C}$ is given by the following:

$$q_{0,T,C} = \frac{wq - B - T}{\alpha p}. \tag{27}$$

The retailer's problem

At time zero of the selling period, the capital-constrained retailer pays B to the manufacturer. At the end of this period, the retailer's revenue is $\alpha p min[D + g(e),q]$ $+ T$, and the retailer is required to repay $min[\alpha p min[D + g(e),q] + T,(wq - B)]$ to the manufacturer. Thus, the retailer needs to choose the optimal order quantity to maximize his or her profit; his or her expected profit is as follows:

$$\begin{aligned} \pi_{r,T,C} = {} & \alpha\left[\int_{q_{0,T,C}-g(e)}^{q-g(e)} p\big(D+g(e)\big) f(D)\,dD + \int_{q-g(e)}^{\infty} pqf(D)\,dD\right] \\ & - \int_{q_{0,T,C}-g(e)}^{\infty} (wq-B-T) f(D)\,dD - B - \frac{1}{2}(1-\theta)ae^2 \end{aligned}. \tag{28}$$

Combining Equation (27) with Equation (28) results in the following:

$$\pi_{r,T,C} = \alpha p\left[q - \int_{q_{0,T,C}-g(e)}^{q-g(e)} F(D)\,dD\right] - wq + T - \frac{1}{2}(1-\theta)ae^2. \tag{29}$$

Proposition 7. *In a decentralized supply chain in which the capital-constrained retailer receives trade credit financing (for the given wholesale price* w *and level of carbon emissions reduction* e*), when* $\alpha p > w$*, the retailer's optimal order quantity* $q_{T,C}{}^{*}$ *satisfies the first-order optimality condition of its expected profit function, which is uniquely given by the following:*

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$$\alpha p\bar{F}\left(q-g\left(e\right)\right)=w\bar{F}\left(q_{0,T,C}-g\left(e\right)\right),\ where\ q_{0,T,C}=\frac{wq-B-T}{\alpha p}. \qquad (30)$$

The manufacturer's problem

At the end of the selling period, the manufacturer will share $(1-\alpha)$ of the retailer's revenue and give an amount T of money to the retailer. When the demand is too low, the retailer will go bankrupt, and all of the revenue will be given to the manufacturer. Since the manufacturer's profit is a function of (w, q, e) and q is the function of w, the manufacturer needs to choose the optimal wholesale price w and level of carbon emissions reduction e to maximize their profit. Thus, when the retailer gets financing from trade credit financing, the manufacturer's expected profit function is as follows:

$$\begin{aligned}\pi_{m,T,C}&=\left(1-\alpha\right)\left[\int_{q_{0,T,C}-g(e)}^{q-g(e)}p\left(D+g\left(e\right)\right)f\left(D\right)dD+\int_{q-g(e)}^{\infty}pqf\left(D\right)dD\right]-cq+B\\&+\int_{0}^{q_{0,T,C}-g(e)}p\left(D+g\left(e\right)\right)f\left(D\right)dD+\int_{q_{0,T,C}-g(e)}^{\infty}\left(wq-B-T\right)f\left(D\right)dD-\frac{1}{2}\left(1-\theta\right)ae^{2}\end{aligned} \qquad . (31)$$

Combining Equation (27) with Equation (31) results in the following:

$$\pi_{m,T,C}=\left(1-\alpha\right)p\left[q-\int_{0}^{q-g(e)}F\left(D\right)dD\right]-\alpha p\int_{0}^{q_{0,T,C}-g(e)}F\left(D\right)dD+\left(w-c\right)q-T-\frac{1}{2}\left(1-\theta\right)ae^{2} \qquad . (32)$$

Supply chain coordinating contract

Under the assumption that the supply chain acts as a centralized system, the manufacturer and retailer will work together to coordinate the supply chain. Under this condition, the supply chain's profit $\pi_{s,T,C}$ equals the manufacturer's profit plus the retailer's profit, which is expressed as follows:

$$\pi_{s,T,C} = \pi_{r,T,C} + \pi_{m,T,C} = p\left[q - \int_0^{q-g(e)} F(D)dD\right] - cq - \frac{1}{2}ae^2. \tag{33}$$

Proposition 8. *In a decentralized supply chain where the capital-constrained retailer gets trade credit financing, coordination can be achieved by designing the contract as* $(w_T, \alpha_T, \theta_T, T_T)$*, which is given by the following:*

$$\alpha c = w\overline{F}\left(\frac{wq - B - T}{\alpha p} - g(e)\right). \tag{34}$$

$$\theta = 1 - \alpha. \tag{35}$$

The decentralized supply chain's optimal order quantity and optimal level of carbon emission reduction $\left(q_{T,C}{}^{*}, e_{T,C}{}^{*}\right)$ *are given by the following:*

$$q_r = \overline{F}^{-1}\left(\frac{c}{p_r}\right) + g(e). \tag{36}$$

$$e = (p - c)\frac{g'(e)}{\theta a}. \tag{37}$$

Comparing Equations (36) and (37) with Equations (12) and (15), we obtained $q_{T,C}{}^{*} > q_T{}^{*}$ and $e_{T,C}{}^{*} > e_T{}^{*}$, showing that the supply chain with a contract outperforms the non-contract supply chain in production quantity and emissions reduction when trade credit financing is viable.

Comparing Equations (36) and (37) with Equations (25) and (26), we obtained $q_{T,C}{}^{*} > q_{B,C}{}^{*}$ and $e_{T,C}{}^{*} > e_{B,C}{}^{*}$, showing that the improvement in production quantity and emissions reduction is more remarkable when trade credit financing is viable.

Conclusions

This paper investigated a green supply chain, which consisted of one manufacturer playing a leading role and one capital-constrained retailer; in this supply chain, bank

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financing and trade credit financing were viable. Considering that customers prefer green products, we assumed that reducing emissions would expand the market size. In this study, we examined the retailer and manufacturer's operating and financing decisions under bank financing and trade credit financing, respectively. We found that the retailer will order more products when the manufacturer invests in emissions reduction. The supply chain achieves a win-win outcome for production quantity and emissions reduction when the manufacturer invests in emissions reduction. Compared with bank financing, the effect is more remarkable when trade credit financing is viable. A combined contract has been proposed to coordinate the supply chain. This shows that a supply chain with a contract outperforms a non-contract supply chain (in terms of production quantity and emissions reduction). The effect is more remarkable when the retailer is financed by the manufacturer. Thus, the economic and environmental performance of the supply chain can be improved in this process.

Appendix

Proof of proposition 1.

From Equation (5), we obtained $\frac{\partial \pi_{r,B}}{\partial q^2} = -pf\left(q-g\left(e\right)\right) < 0$. Thus, the retailer's expected profit function is a concave with regard to(w.r.t.), q_r, and the optimal order quantity is given by the following:

$$\frac{\partial \pi_{r,B}}{\partial q} = p\bar{F}\left(q-g\left(e\right)\right) - w\left(1+r_f\right) = 0,$$

This can also be expressed as follows:

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$$q_r = \bar{F}^{-1}\left(\frac{w\left(1+r_f\right)}{p_r}\right) + g\left(e\right).$$

Proof of proposition 2.

By substituting Equation (6) into (7) when $\frac{\partial \pi_{m,B}}{\partial w} = 0$ and $\frac{\partial \pi_{m,B}}{\partial e} = 0$, we obtained the following:

$$\bar{F}^{-1}\left(\frac{w\left(1+r_f\right)}{p_r}\right) + g\left(e\right) - \frac{\left(w-c\right)\left(1+r_f\right)}{pf\left(\frac{w\left(1+r_f\right)}{p_r}\right)} = 0,$$

$$e = \frac{\left(w-c\right)g'\left(e\right)}{\theta a}.$$

Substituting the above equations into Equation (7), we obtained the following:

$$\frac{\partial^2 \pi_{m,B}}{\partial w^2} = -\frac{\left(1+r_f\right)}{pf\left(q-g\left(e\right)\right)} < 0, \text{ the Hessian matrix } H < 0.$$

Hence, the manufacturer's profit function is a concave w.r.t., w_B and e_B. The optimal wholesale price, production quantity, and level of carbon emissions reduction are given by $\frac{\partial \pi_{m,B}}{\partial w} = 0$ and $\frac{\partial \pi_{m,B}}{\partial e} = 0$.

Proof of proposition 3.

From Equation (11), the first-order optimality condition of the retailer's expected profit function can be expressed by the following:

$$\frac{\partial \pi_{r,T}}{\partial q} = p\bar{F}\left(q-g\left(e\right)\right) - w\bar{F}\left(q_{0,T}-g\left(e\right)\right) \text{ where } q_{0,\mathrm{T}} = \frac{\left(wq-B\right)}{p}.$$

The second-order optimality condition of the retailer's expected profit function can be

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expressed by the following:

$$\frac{\partial^2 \pi_{r,T}}{\partial q^2} = \left[\frac{w^2}{p} f\left(q_{0,T} - g(e)\right) - pf\left(q - g(e)\right)\right].$$

From $q_{0,T} < q_r$ and $\frac{f(D)}{\bar{F}(D)}$ increasing in D, we obtained the following:

$$\frac{f\left(q_{0,T} - g(e)\right)}{\bar{F}\left(q_{0,T} - g(e)\right)} < \frac{f\left(q - g(e)\right)}{\bar{F}\left(q - g(e)\right)}.$$

When $\frac{\partial \pi_{r,T}}{\partial q} = 0$,

$$\frac{w^2}{p} f\left(q_{0,T} - g(e)\right) < pf\left(q - g(e)\right).$$

Thus, $\frac{\partial^2 \pi_{r,T}}{\partial q^2} < 0$, the retailer's expected profit function is a concave w.r.t., q_r, and the optimal order quantity can be given by the following:

$$\frac{\partial \pi_{r,T}}{\partial q} = p\bar{F}\left(q - g(e)\right) - w\bar{F}\left(q_{0,T} - g(e)\right) = 0 \text{ where } q_{0,\mathrm{T}} = \frac{(wq - B)}{p}.$$

This can also be expressed as follows:

$$p\bar{F}\left(q - g(e)\right) = w\bar{F}\left(q_{0,T} - g(e)\right), \textit{ where } q_{0,\mathrm{T}} = \frac{(wq - B)}{p}.$$

Proof of proposition 4.

By substituting Equation (12) into Equation (13), when $\frac{\partial \pi_{m,T}}{\partial w} = 0$ and $\frac{\partial \pi_{m,T}}{\partial e} = 0$, we obtained the following:

$$\frac{p\bar{F}\left(q - g(e)\right)\left[1 - qh\left(q - g(e)\right)\right]}{1 - \frac{wq}{p} h\left(q_{0,T} - g(e)\right)} - c = 0,$$

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$$e=\left[\frac{\left(p^2-\frac{p^3}{w}\right)\bar{F}\left(q-g\left(e\right)\right)+c\left(w-\frac{w^2}{p}\right)f\left(q_{0,T}-g\left(e\right)\right)}{\left[pf\left(q-g\left(e\right)\right)-\frac{w^2}{p}f\left(q_{0,T}-g\left(e\right)\right)\right]}+p-c\right]\frac{g'\left(e\right)}{a}.$$

Substituting the above equations into Equation (13), we obtain the following:

$\frac{\partial^2\pi_{m,T}}{\partial w^2}<0$, the Hessian matrix of the manufacturer's profit function $H<0$

Hence, the manufacturer's profit function is a concave w.r.t., w_T and e_T. The optimal wholesale price, production quantity, and level of carbon emissions reduction can be given by $\frac{\partial\pi_{m,T}}{\partial w}=0$ and $\frac{\partial\pi_{m,T}}{\partial e}=0$.

Proof of proposition 5.

From Equation (19), we obtained $\frac{\partial^2\pi_{r,B,C}}{\partial q^2}=-\alpha pf\left(q-g\left(e\right)\right)<0$. Thus, the retailer's expected profit function is a concave w.r.t., q_r, and the optimal order quantity can be given by the following:

$$\frac{\partial\pi_{r,B,C}}{\partial q_r}=\alpha p\bar{F}\left(q-g\left(e\right)\right)-w\left(1+r_f\right)=0,$$

This can also be expressed as follows:

$$q=\bar{F}^{-1}\left(\frac{w\left(1+r_f\right)}{\alpha p}\right)+g\left(e\right).$$

Proof of proposition 6.

From Equation (22), when $\frac{\partial\pi_{s,B,C}}{\partial q}=0$ and $\frac{\partial\pi_{s,B,C}}{\partial e}=0$, we obtained the following:

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$$q = \bar{F}^{-1}\left(\frac{c + wr_f}{p}\right) + g(e),$$

$$e = \left[p - c - wr_f\right]\frac{g'(e)}{a}.$$

Substituting the above equations into Equation (22) results in the following:

$$\frac{\partial^2 \pi_{s,B,C}}{\partial q^2} = -pf\left(q - g(e)\right) < 0,$$

the Hessian matrix $H = -apf\left(q - g(e)\right) < 0$.

Hence, the supply chain's expected profit is a concave w.r.t., q_r and *e*. The optimal order quantity, production quantity, and level of carbon emissions reduction can be given by $\frac{\partial \pi_{s,B,C}}{\partial q} = 0$ and $\frac{\partial \pi_{s,B,C}}{\partial e} = 0$.

When $w = \frac{\alpha c}{1 + r_f - \alpha r_f}$ and $\theta = 1 - \alpha$, we obtained the following:

$$\pi_{r,B,C} = \alpha \pi_{s,B,C} + (1-\alpha) Br_f + T - \alpha A$$

$$\pi_{m,B,C} = (1-\alpha)\pi_{s,B,C} - (1-\alpha) Br_f - T + \alpha A$$

Under this condition, the retailer's optimal order quantity and level of carbon emissions reduction are the same as the centralized supply chain.

Proof of proposition 7.

As with the proof of proposition 3, we obtained the following:

$$\frac{w^2}{\alpha p} f\left(q_{0,T,C} - g(e)\right) < \alpha pf\left(q - g(e)\right)$$

From Equation (29), we obtained the following:

$$\frac{\partial^2 \pi_{r,T,C}}{\partial q^2} = \left[\frac{w^2}{\alpha p} f\left(q_{0,T,C} - g(e)\right) - \alpha pf\left(q - g(e)\right)\right] < 0$$

Thus, the retailer's expected profit function is a concave w.r.t., q_r, and the optimal order quantity can be given by the following:

$$\alpha p\bar{F}\left(q-g\left(e\right)\right)=w\bar{F}\left(q_{0,T,C}-g\left(e\right)\right),\ where\ q_{0,T,C}=\frac{wq-B-T}{\alpha p},$$

$$\frac{\partial\pi_{r,T,C}}{\partial q}=\alpha p\bar{F}\left(q-g\left(e\right)\right)-w\bar{F}\left(q_{0,T,C}-g\left(e\right)\right)\text{ where }q_{0,T,C}=\frac{wq_r-B-T}{\alpha p_r},$$

This can also be expressed as follows:

$$\alpha p\bar{F}\left(q-g\left(e\right)\right)=w\bar{F}\left(q_{0,T,C}-g\left(e\right)\right),\ where\ q_{0,T,C}=\frac{wq-B-T}{\alpha p}.$$

Proof of proposition 8.

As with the proof of proposition 6, we knew that the supply chain's expected profit is a concave w.r.t., q_r and e. The optimal order quantity, production quantity, and level of carbon emissions reduction can be given by $\frac{\partial\pi_{s,T,C}}{\partial q_r}=0$ and $\frac{\partial\pi_{s,T,C}}{\partial e}=0$.

When $\alpha c=w\bar{F}\left(\frac{wq-B-T}{\alpha p}-g\left(e\right)\right)$ and $\theta=1-\alpha$,

defining $K\left(q\right)=\alpha p\int_0^{q_{0,T,C}-g(e)}F\left(D\right)dD-wq+\alpha cq$,

from $K'\left(q\right)=0$ and $K\left(\frac{\alpha pg\left(e\right)+B+T}{w}\right)=0$, we have

$$\alpha p\int_0^{q_{0,T,C}-g(e)}F\left(D\right)dD-wq=-\alpha cq.$$

Thus,

$$\pi_{r,T,C}=\alpha\pi_{s,T,C}+T-\alpha A.$$

Under this condition, the retailer's optimal order quantity and carbon emissions reduction level are the same as in the centralized supply chain.

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