Green financing strategies in a low-carbon e-commerce supply chain under service quality regulation

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Abstract
Green financing is an effective means to encourage small and medium-sized enterprises (SMEs) to improve environmental efficiency in their operations. This paper studies two financing strategies of a carbon-dependent manufacturer in an e-commerce supply chain, which are called bank credit and cost-sharing with third-party platform that provides a marketplace. The optimal carbon emission reduction (CER) level, selling price, and service level are investigated. It turns out that the participants’ profits and environmental benefit under two financing strategies are higher than those without financing. In addition, when the commission provided by the platform is low, the manufacturer is more inclined to bank credit, and when the commission is high, it is more sensible to share CER cost with the platform. The impact of government service supervision policies on corporate decision-making is further explored. The results prove that setting an appropriate service threshold and reward-penalty factor is not only conducive to incentivizing the platform to improve service level but also beneficial to the environment and overall social welfare. This paper provides cooperation strategies for manufacturers in green financing in the e-commerce supply chain and provides policy recommendations for the government to implement e-commerce service regulation and promote CER.

Keywords CER level · Bank credit · Cost sharing · Green financing · Service regulation

Introduction
With the popularization of the mobile Internet and high efficiency of logistics, more and more consumers are more inclined to shop through online channels. According to the large database of “Dianshubao” (DATA.100EC.CN), the scale of online shopping users has exceeded 800 million in 2020, and the domestic online retail market transaction scale in the first half of 2020 has reached 5.36 trillion yuan, accounting for 31.1% of China’s total retail sales of consumer goods1. The huge potential market and the low threshold of e-commerce operations attracted a large number of enterprises to enter the e-commerce market, and the supply chain composed of a platform and SMEs is a mainstream business mode (Qin et al. 2020). In order to remain competitive, SMEs have to continually increase investment in advertising, products and services, etc. For carbon-dependent online SMEs (such as fashion industry and daily necessities companies), in addition to basic production costs, increasing investment in CER technology is the key to attracting consumers with low-carbon preferences. But the innovation of low-carbon products is undoubtedly a high expenditure (Cao and Yu, 2018). The Japanese clothing brand Uniqlo announced in 2019 that it would start making clothing from recycled plastic bottles to create as many environmentally friendly products as possible and launch environmentally friendly clothing in 2020, while this plan has also been shelved affected by COVID-19 (Kumagai and Nagasawa 2020).

In order to encourage enterprises to invest in CER and alleviate financial pressure, the government has proposed

1 http://www.100ec.cn/zt/2020slsdsbg/
various subsidy policies (such as CER subsidies; green consumption subsidies; recycling subsidies), and banks around the world have also launched green finance (An et al. 2020). Green finance refers to a series of financial services provided to improve the environment, mitigate climate change, and efficiently use resources (Qin et al. 2018). The green finance mentioned in this paper mainly refers to the green credit services provided by banks for companies that actively invest in CER. According to a report in China Banking and Insurance News, as of the end of 2018, the six major state-owned banks had invested more than 4.4 trillion yuan in energy conservation and environmental protection projects, including CER. It can be seen that the state’s support for green finance has attracted many enterprises to invest in low-carbon products through bank loans.

Many third-party platforms, not only act as participants to display product information and provide logistics services, but also play the role of financiers, providing financial support for upstream and downstream enterprises. For example, Amazon, Taobao, and JD.com all provide financing services to SMEs operating on them (Wang et al. 2019a). In addition to collecting transaction commissions from online enterprises, such platforms can also earn financing interest, but correspondingly need to bear a certain capital cost. Undoubtedly, the commissions and investment schemes provided by the platform will surely affect the operation and financing choices of SMEs.

On the other hand, with the emergence of various e-commerce platforms and fierce competition, the quality of services provided by the platform is also difficult to guarantee in a short time. A Chinese e-commerce brand Pinduoduo was interviewed by the national regulatory authority in August 2018, requesting rectification of platform operations; in November 2019, the State Administration for Market Regulation interviewed more than 20 platform companies such as JD.com, Meituan, and Alibaba, and pointed out their service quality control over a series of issues such as false propaganda, personal information leakage, and the sale of fake and shoddy products was unqualified. In response to this series of irregularities, how the regulatory authorities should further improve regulatory policies and promote the sound development of the online retail industry is a serious issue.

We construct an e-commerce supply chain consisting of a carbon-dependent and capital-constrained SME (referred to as a manufacturer in this paper) and a third-party platform, where the manufacturer has two financing options, green credit from bank and CER cost sharing with platform, and further consider the situation where the service quality of the e-commerce platform is supervised by the government. This paper focuses on solving the following questions:

1. How will manufacturers decide on CER level and selling price under different financing strategies? And how will the platform operate both as a participant and as a financier?
2. How should manufacturers choose between the two strategies of bank credit and cost sharing? And what are the conditions under which the platform is willing to share the CER cost with the manufacturer?
3. How does service quality supervision affect the decision-making of the platform and other participants in the supply chain?

The main contributions of this paper are as follows. First of all, in view of the current sparse research on green financing in the e-commerce industry, this paper establishes decision models for an e-commerce supply chain under the three scenarios of no financing, bank credit, and CER cost sharing with the platform, and the optimal CER level, selling price, and service level are obtained. Secondly, this paper analyzes the manufacturer’s financing preference for bank credit and cost-sharing with the platform, as well as the platform’s willingness to invest in CER, and finds that commission is an important factor affecting financing choices. This paper explores a way for manufacturers to reduce carbon emissions and green financing in the e-commerce supply chain and provides conditions for manufacturers to cooperate with e-commerce platforms to reduce emissions. Finally, this paper considers the impact of service quality supervision on supply chain enterprises and finds that service regulation can not only urge e-commerce platforms to improve service levels, thereby boosting demand, but also prompt manufacturers to increase their CER levels. This is not only beneficial to enterprises but also beneficial to the environment and increases the overall social welfare. Therefore, regulators can effectively regulate the services of e-commerce platforms by setting a minimum service quality threshold or reward-penalty factor.

The rest of this paper is organized as follows. “Literature review” reviews the relevant literature. “Model description” describes the model framework. The optimal decisions of supply chain members considering multiple financing strategies and service supervision are investigated in “Models without service regulation” and “Models with service regulation,” respectively. “Discussions and numerical analysis” compares different financing strategies and service quality supervision policies, as well as sensitivity analysis. “Conclusions” summarizes the main conclusions and gives an outlook on the future research. All detailed proofs are shown in the Appendix.

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2 http://xx.sinoins.com/2019-06/06/content_293691.htm
3 http://www.kuaimai.com/dsnews/658.html
4 http://china.qianlong.com/2019/1106/3437724.shtml
Literature review

The research in this paper is mainly related to the following three streams: decisions of e-commerce supply chain, supply chain finance, and government supervision of supply chain enterprises. In this section, we will review the existing literature and highlight the research focus of this paper.

Decisions of e-commerce supply chains

The research of e-commerce supply chain initially focused on dual channels, in which online channel is regarded as an emerging business mode for the purpose of market development (Chen 2015; Lu and Liu 2015; Batarfi et al. 2016; Xu et al. 2021). Then the popularity of environmental awareness prompted researchers to consider the impact of the government’s CER regulation on the e-commerce industry and consumers’ low-carbon preferences on online operators. By incorporating online channel, Ji et al. (2017) explored the impact of cap-and-trade mechanism and consumers’ low-carbon preference on the respective carbon emission reduction decisions of manufacturer and retailer in a dual-channel supply chain. The influence of cap-and-trade and low-carbon preference in the stochastic demand environment is further studied in Ghosh et al. (2020). Ranjan and Jha (2019) investigated the optimal green quality level and sales effort level of a dual-channel supply chain where a manufacturer sells green products through online channel and non-green products through offline channel. In terms of closed-loop supply chain, Xie et al. (2018) studied the service effort level of a retailer responsible for reverse recycling in a dual-channel closed-loop supply chain based on the phenomenon of poor-quality recycling. Wang et al. (2020c) analyzed recycling decisions of an e-commerce closed-loop supply chain in which a remanufacturer has altruistic preferences under government subsidy policy. On this basis, Wang et al. (2021c) further investigated the impact of the government’s reward-penalty regulation and altruistic preference on the decision-making of an e-commerce closed-loop supply chain composed of a remanufacturer and a network recycling platform.

In addition, some researchers considered the operational decisions of pure online enterprises, taking into account environmental factors. For example, Ding and Jin (2019) studied the optimal service response time for an online retailer, where fast response time not only requires high costs but also generates high carbon emissions. But they only focused on the traditional supply chain structure, that is, suppliers, manufacturers, or retailers, and this paper considers another mainstream e-commerce mode, namely e-commerce platforms. Wang et al. (2020b) constructed a green e-commerce supply chain consisting of a manufacturer and an e-commerce platform, but mainly studied the impact of the manufacturer’s fairness preference on decision-making. Different from Han and Wang (2018) and Han et al. (2020), which emphasized carbon emission reduction decisions and coordination of an online manufacturer in a low-carbon environment, this paper considers how a capital-constrained manufacturer makes CER and price decisions in e-commerce operations.

Supply chain finance

Supply chain finance involves scenarios where supply chain members consider their own financial capabilities in operational decisions. Some literature proposed various coordination solutions for supply chain members with limited funds. Kouvelis and Zhao (2016) separately analyzed the impact of the three contracts of revenue sharing, buyback, and quantity discount on a supply chain where both supplier and retailer are subject to capital constraints. Based on this, Xiao et al. (2017) designed a new contract to allocate profits between a leading supplier and a capital-constrained retailer. There is also some literature comparing the pros and cons of different financing strategies. Kouvelis and Zhao (2012) studied a newsvendor-like retailer’s preference for supplier financing and bank financing and found that by designing a trade credit contract, the retailer would prefer supplier financing. Gao et al. (2018) investigated the impact of financing from an online peer-to-peer lending platform on supply chain decisions under uncertain demand, considering two scenarios where the manufacturer and retailer are subject to financial constraints, respectively. Li et al. (2018) analyzed a capital-constrained retailer’s preference for the two strategies of partial credit guarantee and trade credit in a supply chain where the supplier is risk-averse. Wang et al. (2019a) discussed two choices of an online retailer for bank financing and e-commerce platform financing, where the platform is divided into two types of conservative and active according to the difference in lending and leasing business. It turns out that the coordinated active e-commerce platform financing is more popular with retailers. Based on general supply chain contracts, Huang et al. (2020) analyzed the optimal decision-making of SMEs in three financing strategies of trade credit, credit guarantee, and repurchase guarantee. However, none of the above literature considers carbon emissions.

Wang and Zhi (2016) demonstrated that green financing is a financial means that can effectively improve the economic and environmental performance of supply chain companies. Wang et al. (2021a) studied the optimal decisions of a capital-constrained manufacturer under the direct selling model and the supply chain model, respectively, where the manufacturer produces both normal products and low-carbon
remanufactured products. The impact of the Carbon Emission Permits Repurchase Strategy on the manufacturer’s decision-making and mode selection was further analyzed. Wang et al. (2021b) considered high-cost pressures for small and medium manufacturers to invest in carbon emission abatement technologies. They assumed that a dominant retailer has altruistic preferences and designed a cost-sharing contract under altruistic preferences. Some other literature also analyzed the preference of supply chain companies for different financing modes in the low-carbon context. Qin et al. (2018) studied the impact of two financing strategies, bank credit and cost-sharing with downstream retailer, on the carbon emission reduction decision of an insufficiently funded manufacturer. Yang et al. (2019) studied decisions and coordination of two capital-limited retailers receiving trade credit from the same manufacturer or external financing. Xu and Fang (2020), An et al. (2020), and Luo et al. (2020) also considered the comparison of internal financing and external financing strategies of supply chain companies in the context of carbon emissions. Different from the above literature, this paper explores green financing strategies of an e-commerce supply chain composed of a carbon-dependent manufacturer and a third-party platform that provides marketplace. In addition to external financing, the willingness of platform to share manufacturer’s CER cost is also discussed.

**Government supervision of supply chain enterprises**

The government’s supervision of the production and operation of supply chain enterprises has always been crucial. The most common is undoubtedly the environmental performance regulations, such as carbon emission capacity (Xu et al. 2018; Ding and Jin 2019; Peng et al. 2020), cap-and-trade (Ghosh et al. 2020), carbon tax (Wang et al. 2017). There is also literature on the impact of government subsidy policies on manufacturers’ green technology investment decisions (Hafezi and Zolfagharinia 2018; Yang et al. 2020; Chen et al. 2021). Moreover, Cao et al. (2018) studied the government’s implementation of regulations and fiscal tools to urge manufacturers in the reverse supply chain to expand extended producer responsibility (EPR). It turns out that proactive and prudent policies should be adopted to encourage remanufacturing. Chen et al. (2021) explored the feasibility of implementing buy-back supervision based on recycling target and reuse target, as well as its impact on consumer surplus, supply chain profits, and social welfare. Javadi et al. (2019) investigated price decisions of a dual-channel supply chain when the return link is subject to government energy-saving supervision. Wang et al. (2020c) analyzed the recycling decisions of a closed-loop e-commerce supply chain considering the government recycling subsidy policy. Chen et al. (2019) studied the impact of price cap regulation on the pricing decision of a manufacturer in a pharmaceutical supply chain. They further analyzed the impact of quality supervision on the equilibriums of two competing pharmaceutical manufacturers (Chen et al. 2020).

A review of the above literature reveals that in addition to basic environmental performance supervision, supervision of supply chain companies’ pricing, extended producer responsibility, recycling quality, and product quality is also of importance. Different from the above literature, this paper studies the government’s supervision of the service quality of a third-party platform that provides the marketplace in an e-commerce supply chain, and the impact of the policy on the decision-making of supply chain members.

**Model description**

The model considers a low-carbon e-commerce supply chain composed of a SME with constrained capital (hereinafter referred to as a “manufacturer”) and a large e-commerce platform (such as JD), where the platform acts as a leader due to its advantage of economic scale (Zhang et al. 2019) and the manufacturer acts as a follower. In order to exploit a low-carbon market and promote sustainable development, the manufacturer vigorously produces low-carbon products and invests in CER technologies with limited capitals, assuming that the CER investment cost is $C(e) = \frac{h e^2}{2}$ and the emission reduction cost coefficient $h = 1$ without affecting the conclusion of the model (Feng et al. 2017). Since we are mainly concerned with the impact of the manufacturer’s capital constraints on the CER decision, the production cost is ignored (Yang et al. 2017; Xu and Fang 2020). Then, the manufacturer publishes product information through the online platform at a selling price $p$. Two financing strategies are discussed in response to the manufacturer’s financial constraints, including an external financing strategy of bank credit loans and an internal financing strategy that shares costs with upstream and downstream companies.

As an interactive medium, the e-commerce platform provides consumers with a series of services $s$ such as product information display, order placement, logistics, etc., and the service cost of the platform $C(s) = ks^2/2$, where $k$ represents the cost required to provide unit service, normalized to 1. On the other hand, after the customer confirms the receipt, the platform will receive the payment and return the remaining earning to the manufacturer after deducting a certain commission $\rho$. Referring to Wang et al. (2019b), the online platform generally has two types of fees, one is a fixed fee related to “basic services,” and the other is a commission related to each transaction, usually at a fixed commission rate. Therefore, this paper assumes that commission is an exogenous variable, and since the fixed fee has no effect on the model, it will not be considered later (Han and Wang 2018; Yan et al. 2019).
The quality of service provided by the platform is discussed in two scenarios. One is that the e-commerce platform is not subject to service quality regulation, and the platform can improve the service level within the scope of internal capital; the other is that the platform is constrained by service quality regulation, in order to further protect the interests of consumers, the regulator sets a minimum service threshold $s_0$, requiring the platform to at least achieve a service level above this level; otherwise, it will be fined $\Delta(s) = h(s_0 - s)$, where $h$ represents reward-penalty factor charged for unit service that does not reach the threshold (Yi and Li 2018; Ding and Jin 2019). The schematic diagram of the model is shown in Fig. 1.

The main parameters involved in the paper are as follows:

- $\alpha$: Total market size
- $p$: Selling price, decision variable
- $\lambda$: The elasticity coefficient of CER level to demand
- $e$: Unit CER level, decision variable
- $\gamma$: The elasticity coefficient of logistics service level to demand
- $s$: Unit logistics service level, decision variable
- $\rho$: Unit commission rate charged by the platform, $0 < \rho < 1$
- $A$: The manufacturer’s capital for investing in carbon reduction
- $r$: The interest rate charged by the bank
- $\eta$: The proportion of carbon reduction costs that the platform shares with the manufacturer, $0 < \eta < 1$
- $s_0$: Service threshold set by the regulator
- $h$: Reward-penalty factor charged for unit service that does not reach the threshold

Consistent with most of the literature (Han and Wang 2018; Yi and Li 2018; Cong et al. 2020), this paper adopts a linear demand function, in which higher CER level and logistics service level will attract more consumers, and the product price is just the opposite. The required function expression is

$$q = \alpha - \beta p + \lambda e + \gamma s$$

(1)

where $\alpha$ represents the total potential market demand, $\beta$ represents the elasticity coefficient of price to demand, $\lambda$ represents the elasticity coefficient of CER level to demand, and $\gamma$ represents the elasticity coefficient of logistics service level to demand. Without affecting the conclusion, we assume that $\beta = 1$ (Yi and Li 2018; Feng et al. 2017), and the demand function is further expressed as $q = \alpha - p + \lambda e + \gamma s$, where $0 < \lambda, \gamma \leq 1 < \alpha$, means that consumers are more sensitive to the price than the CER level and service level.

Based on the above assumptions, in order to further explore the impact of service supervision implemented by regulators on other stakeholders in society, we define the function of consumer surplus (CS) and social welfare (SW) as
CS = \int_{\eta_{\text{min}}}^{\eta_{\text{max}}} q(\eta, e, s) d\eta = \int_{\eta}^{\eta_{\text{max}}} (a - \beta e + \xi_1) d\eta = \frac{(a - \beta p + \xi_1)^2}{2\beta}. \tag{2}

SW = \pi_p + \pi_m + CS + h(s_0 - s)q \tag{3}

where \( \bar{p}e(\rho, \frac{a + \lambda e + \xi_1}{\beta}) \) is the price variable (Sinayi and Rasti-Barzoki 2018; Wang et al. 2020a).

In order to ensure that each scenario is solvable, we assume that the model parameters satisfy:

\[ A \leq \frac{\sigma^2 - \beta^2(1 - \rho)^2}{2[B^2 - 2\rho^2(1 + \rho)]^2}, \]

where \( B = 2 + 2r - \lambda^2(1 - \rho) \), and the inequality means that it is inevitable for the manufacturer to be trapped by financial constraints when improving current operational decisions.

**Models without service regulation**

In this section, we do not consider service supervision of the online platform by the regulator, and analyzes three financing strategies of a low-carbon manufacturer under the capital constraint, including benchmark model-no financing (UN), loaning from the bank (UB), and sharing the cost with the platform (UP). For the sake of the exposition, the optimal solutions to the model are represented by the superscript *, and the subscripts m and p respectively represent the manufacturer and the platform.

**No financing (UN)**

In the scenario of no financing, the manufacturer’s investment in CER technology must not exceed its capital constraint \( A \). Thus, the platform’s profit function and manufacturer’s profit function are expressed as follows:

\[
\begin{align*}
\pi_p^{\text{UN}}(s) &= \rho pq - \frac{1}{2} e^2 \tag{4} \\
\pi_m^{\text{UN}}(s, e) &= (1 - \rho) pq - \frac{1}{2} e^2 \tag{5}
\end{align*}
\]

s.t. \( \frac{1}{2} e^2 \leq A \)

According to the reverse induction method (Wang et al. 2019b), we first analyze the manufacturer’s optimal solutions with respect to the service level \( s \)

\[
\begin{align*}
\bar{e}^{\text{UN}} &= \sqrt{2A} \\
\bar{p}^{\text{UN}} &= \frac{1}{2}(a + sy + \lambda \sqrt{2A})
\end{align*}
\]

And the following lemma is deduced.

**Lemma 1** When the manufacturer does not finance, (1) the optimal CER level is only relevant to \( \lambda \); (2) the optimal selling price is positively related to \( s \) and \( A \).

Lemma 1 highlights the importance of enterprises’ funds in their CER level and price decision-making and also verifies the value of this paper.

**Proposition 1** Under the UN strategy, the platform’s optimal service level is

\[
s_{\text{UN}}^* = \frac{\lambda \rho (a + \sqrt{2A})}{2 - \rho^2}
\]

The manufacturer’s optimal CER level and selling price are

\[
\begin{align*}
\bar{e}_{\text{UN}}^* &= \sqrt{2A} \\
\bar{p}_{\text{UN}}^* &= \frac{a + \lambda \sqrt{2A}}{2 - \rho^2}
\end{align*}
\]

The optimal profits of platform and manufacturer are

\[
\begin{align*}
\pi_p^{\text{UN}} &= \frac{\rho [a + \lambda \sqrt{2A}]^2}{4 - 2\rho^2} \\
\pi_m^{\text{UN}} &= \frac{(a + \lambda \sqrt{2A})^2 (1 - \rho)}{(2 - \rho^2)^2} - A
\end{align*}
\]

The following lemma about the impact of various factors on decisions can be obtained intuitively.

**Lemma 2**

\[
\begin{align*}
(1) \frac{\partial \pi_p^{\text{UN}}}{\partial \rho} > 0, \frac{\partial \pi_m^{\text{UN}}}{\partial \rho} > 0; (2) \frac{\partial \pi_p^{\text{UN}}}{\partial A} > 0, \frac{\partial \pi_m^{\text{UN}}}{\partial A} > 0, \frac{\partial \pi_m^{\text{UN}}}{\partial A} > 0
\end{align*}
\]

Lemma 2 (1) indicates that the increase in commission will increase the service level and selling price because the commission charged by the platform increases, more funds will be invested to improve the service, while for the manufacturer, the increase in commission makes its cost increases, so it is necessary to raise the selling price to increase its marginal profit. Lemma 1(2) shows that as the manufacturer’s fund increases, not only the selling price and CER level increase but also the platform’s service level. This can be explained by the fact that a large amount of funds prompts the manufacturer to invest more in CER, which stimulates the market’s demand for low-carbon products, and in turn encourages the platform to improve the service level. Therefore, in order to reduce the carbon emission in the production process, the government can increase the
CER level of enterprises by granting financial subsidies to manufacturers.

Bank credit financing (UB)

A common method of external financing is for companies to borrow money from banks on their own credit. (Xu and Fang 2020; Cong et al. 2020). First, the bank announces the interest rate $r$, and then the manufacturer borrows $\left(\frac{1}{2}e^2 - A\right)$ from the bank, which is the CER cost after subtracting the capital $A$, and repays the bank $(1 + r)\left(\frac{1}{2}e^2 - A\right)^+$ at the end of the sales period. At this time, the platform’s profit function and manufacturer’s profit function are expressed as follows:

$$
\kappa_p^{UB}(s) = \rho pq - \frac{1}{2}s^2 \quad (6)
$$

$$
\kappa_m^{UB}(p, e) = (1 - \rho)pq - \frac{1}{2}e^2 - r\left(\frac{1}{2}e^2 - A\right)^+ \quad (7)
$$

The manufacturer’s optimal solutions about the service level $s$ can be obtained

$$
\sigma^{UB} = \frac{(a + \rho)(1 - \rho)}{2 + 2a - 2ri}\left(\frac{1 - \rho}{1 + \rho + r}\right)\left(\frac{1 - \rho}{1 + \rho + r}\right)\left(\frac{1 - \rho}{1 + \rho + r}\right)
$$

Lemma 3 Under the UB strategy, both the CER level and selling price are positively related to $s$, but irrelevant to $A$.

Lemma 3 shows that under the bank credit strategy, the manufacturer does not have to worry about insufficient funds, that is, enough funds can be allocated for CER investments. At this time, as a follower, the manufacturer mainly sets the corresponding CER level and price level referring to the service level of the platform.

Proposition 2 Under the UB strategy, the platform’s optimal service level is

$$
s^{UB*} = \frac{2\rho(1 + r)}{B^2 - 2\rho r^2(1 + r)^2}
$$

The manufacturer’s optimal CER level and selling price are

$$
e^{UB*} = \frac{aB(1 - \rho)}{B^2 - 2\rho r^2(1 + r)^2}
$$

The optimal profits of platform and manufacturer are

$$
r^{UB*}_p = \frac{\rho e^{2(1 + r)^2}}{B^2 - 2\rho r^2(1 + r)^2}
$$

$$
r^{UB*}_m = Ar + \frac{\rho e^{2(1 + r)^2}}{2[B^2 - 2\rho r^2(1 + r)^2]}
$$

Similarly, through intuitive analysis of Proposition 2, we can get the impact of various influencing factors on the optimal decisions under the bank credit financing strategy.

Lemma 4

(1) $\frac{\partial e^{UB*}}{\partial \rho} > 0, \frac{\partial e^{UB*}}{\partial p} > 0, \frac{\partial e^{UB*}}{\partial r} < 0, \frac{\partial e^{UB*}}{\partial r} < 0,$

What is inconsistent with Lemma 2 is that under the bank credit strategy, the CER level is negatively correlated with the unit commission, which is because when the manufacturer’s disposable funds are certain, a higher commission will aggravate the manufacturer’s operating costs, and the corresponding funds invested in CER will be cut back. In addition, with the increase in bank interest rate, not only the CER level and selling price decrease, but also the service level of the platform. This reflects that the manufacturer’s adoption of external financing to solve the financial constraints will affect the operation of the platform, which further provides the possibility of reaching a cost-sharing strategy for both parties.

Proposition 3

(1) $s^{UB*} > s^{UN*}, p^{UB*} > p^{UN*}, e^{UB*} > e^{UN*}$

Proposition 3 shows that the manufacturer’s credit loan from the bank is conducive to solving its own shortage of funds. Under the bank credit loan strategy, the manufacturer has sufficient funds to invest in emission reductions, so the selling price and CER level will increase, which is beneficial to both economic and environmental benefits. Moreover, the service level of the e-commerce platform under the bank’s credit strategy will also be improved, which is because the rise in selling price will increase the total commission charged by the platform, and more funds will be allocated to improve the service level. This indirectly reflects that the manufacturer’s shortage of funds is also detrimental to the platform’s operation and provides the possibility for cooperation between the two parties. Therefore, manufacturers should actively seek financial support from third-party banks or cooperative e-commerce platforms, which are beneficial
to all parties. In addition to subsidies, the government can also encourage commercial banks to cooperate in financing with manufacturing companies that want to carry out green innovation.

**Sharing CER cost with the platform (UP)**

In the internal financing strategies, one approach is to share costs with upstream and downstream enterprises. As the degree of CER increases, it is beneficial to increase the market demand for low-carbon products and thus increase the profitability of the platform. Therefore, this paper assumes that the platform is motivated to share the CER cost by a proportion of $\eta$ with the manufacturer, and at the same time, the remaining CER cost to be paid by the manufacturer should not exceed the financial constraint $A$. Then, the profit of the platform and the manufacturer is

$$\pi^p_{UP}(s, \eta) = \rho p q - \frac{1}{2} s^2 - \frac{\eta}{2} e^2$$  \hspace{1cm} (8)

$$\begin{align*}
\pi^m_{UP}(p, e) &= (1 - \rho)p q - \frac{(1 - \eta)}{2} e^2 \\
\text{s.t.} \quad (1 - \eta) e^2 &\leq A
\end{align*}$$

The manufacturer’s optimal solutions with respect to the service level $s$ and cost-sharing ratio $\eta$ can be obtained

$$e^*_{UP} = \sqrt{\frac{2A}{1-\eta}}$$

$$p^*_{UP} = \left\{ \begin{array}{ll}
\sqrt{\frac{2A}{1-\eta}} & \text{if } \eta \leq \frac{1}{2}
\\
\frac{1}{2} \left( a + s\eta + \lambda \sqrt{\frac{2A}{1-\eta}} \right) & \text{otherwise}
\end{array} \right.$$ 

**Lemma 5** Under the CER cost-sharing strategy, (1) the optimal CER level is irrelevant to $s$, but positively correlated with $A$ and $\eta$; (2) the optimal selling price is positively correlated with $s$, $A$, and $\eta$.

From Lemma 5, we conclude that under the CER cost-sharing strategy, the optimal CER level depends on the amount of funds that the manufacturer can invest, which is similar to Lemma 1. The difference is that the greater the proportion of the cost shared by the platform, the lower the single CER cost that the manufacturer needs to invest, so the total capital $A$ can get a greater degree of application. In addition, as the cost-sharing ratio increases, the manufacturer needs to increase its marginal profit in order to make up for the cost of the platform, and the corresponding total commission fees charged by the platform will also increase.

**Proposition 4** Under the UP strategy, the platform’s optimal cost-sharing ratio and service level is

$$\eta^*_{UP} = 1 - \frac{2A(2 - \sqrt{\frac{2A}{1-\eta}})}{\sqrt{\frac{2A}{1-\eta}}^2}$$

$$s^*_{UP} = \frac{\alpha p r}{2(\sqrt{\frac{2A}{1-\eta}})^2}$$

The manufacturer’s optimal CER level and selling price are

$$e^*_{UP} = \left( \frac{\alpha p r}{\sqrt{\frac{2A}{1-\eta}}^2} \right)$$

$$p^*_{UP} = \left( \frac{\alpha p r}{2(\sqrt{\frac{2A}{1-\eta}})^2} \right)$$

The optimal profits of platform and manufacturer are

$$\pi^p_{UP} = A + \left( \frac{\alpha p r}{\sqrt{\frac{2A}{1-\eta}}^2} \right)$$

$$\pi^m_{UP} = \left( \frac{\alpha p r}{2(\sqrt{\frac{2A}{1-\eta}})^2} \right) - A$$

The following lemma can be concluded.

**Lemma 6**

$$(1) \frac{\partial \pi^p_{UP}}{\partial s} > 0, \frac{\partial \pi^m_{UP}}{\partial s} > 0, \frac{\partial \pi^m_{UP}}{\partial \eta} > 0, \frac{\partial \pi^m_{UP}}{\partial A} < 0; (2) \frac{\partial \pi^p_{UP}}{\partial p} > 0, \frac{\partial \pi^m_{UP}}{\partial p} > 0.$$

It can be found that the platform will weigh the market demand for low-carbon products and services when deciding on the cost-sharing ratio. The greater the demand, the more actively the platform will share CER cost with the manufacturer. In addition, the higher the unit commission charged, the platform will naturally be more willing to share the cost. The less the self-sustaining capital of the manufacturer, the lower the willingness of the platform to share the cost, which is because the less the capital of the manufacturer, from a risk perspective, means the greater the risk of investing in CER, so the platform will reduce its own investment. Therefore, in order to promote the platform to share more costs, the manufacturer can try to promote the low-carbon attributes of products and high-quality services to attract more consumers. Interestingly, from Lemma 6(2), under the cost-sharing strategy, the manufacturer’s CER level is positively correlated with the commission charged by the platform, which is completely different from Lemma 2 and 4. According to Lemma 5 and 6, we can know that the CER level is positively related to the cost-sharing ratio of the platform, and the ratio increases as the commission charged increases. Therefore, the higher the commission, the more willing the platform to invest in CER, so that the CER level can be increased. This indicates that the formulation of the commission contract between the manufacturer and the platform has a significant impact on the CER cost sharing between the two parties. In order to achieve higher levels of CER, the manufacturer can appropriately relax the upper limit on the acceptance of commission.
Proposition 5

\[(1) \quad s_{UP}^* > s_{UN}^*, \quad p_{UP}^* > p_{UN}^*, \quad e_{UP}^* > e_{UN}^*; \quad (2) \quad \lambda_{p} > \lambda_{m} > 0.\]

This proposition shows that cost sharing with the platform can also effectively solve the shortage of funds for the manufacturer. When the platform is willing to share the CER cost with the manufacturer, the amount of funds available to the manufacturer will increase, and the CER level will be improved accordingly, which in turn promotes greater profit for manufacturer and environmental benefit. In addition, the increase in CER level will increase the market’s demand for low-carbon products, which is also beneficial to platform operations. Therefore, cooperative CER is profitable for both the manufacturer and e-commerce platform, and the manufacturer should vigorously promote the benefits of CER and attract investment from upstream and downstream of the supply chain. The e-commerce platform should also take the initiative to help upstream manufacturing companies overcome technical challenges in CER and actively share investment costs.

Models with service regulation

Under service supervision, the regulator will set a service threshold \(s_0\) and implement a unit reward-penalty factor \(h\) when the unit service provided by the platform is lower than \(s_0\). On the contrary, when the service level of the platform exceeds \(s_0\), \(h\) represents the regulator’s unit reward for service. In this context, what will happen to the platform’s operational decision and the manufacturer’s financing strategy is the focus of the following research.

No financing (RN)

The manufacturer’s decision model in this scenario is similar to Section 4.1, except that the platform needs to consider an additional service supervision fee. The profit functions in this scenario are as follows

\[\pi_p^{RN}(s) = \rho pq - \frac{1}{2} s^2 - h(s_0 - s) q\]

\[\pi_m^{RN}(p, e) = (1 - \rho) pq - \frac{1}{2} e^2\]

s.t. \(\frac{1}{2} e^2 \leq A\)

Proposition 6

Under the RN strategy, the platform’s optimal service level is

\[s_{RN}^* = \frac{(a + \sqrt{2A}) (h \gamma + \rho) - h s_0 \gamma}{2 - \rho \gamma^2 - 2h \gamma}\]

The manufacturer’s optimal CER level and selling price are

\[e_{RN}^* = \sqrt{2A}\]

\[p_{RN}^* = \frac{(a + \sqrt{2A}) (2 - h \gamma - h s_0 \gamma^2)}{2(2 - \rho \gamma^2 - 2h \gamma)}\]

The optimal profits of platform and manufacturer are

\[\pi_p^{RN*} = \pi_m^{RN*} = \pi_p^{UN*} > \pi_m^{UN*}\]

Proposition 7

By analyzing the abovementioned optimal equilibriums, the following propositions about the impact of various factors on decisions can be obtained intuitively.

(1) \(\frac{\partial \pi_p^{RN*}}{\partial s_0} < 0, \frac{\partial \pi_p^{RN*}}{\partial h} < 0, \frac{\partial \pi_p^{RN*}}{\partial \rho} < 0; (2) \pi_p^{RN*} > \pi_m^{RN*}\]

From Proposition 7(1), it can be seen that when the regulatory agency supervises the service of the e-commerce platform and the manufacturer does not finance, the service threshold will inhibit the service level and selling price, while the effect of the unit reward-penalty factor is just the opposite. This is because the higher the service threshold, the harder the platform will try to improve the service level in order to avoid fines, and the higher the service cost. When the service threshold is fixed, the higher the unit reward-penalty factor means that the platform is more likely to receive additional rewards for improving the service level. Therefore, when formulating service supervision policies, regulators can set the service threshold appropriately low, and focus more on raising the set value of the reward-penalty factor to achieve a better urging effect. According to Proposition 7(2) and (3), the regulator’s service supervision on the platform will not affect the manufacturer’s CER decision, but it will increase the service level and selling price, and further increase the profits of each participant. This also reflects that service supervision can play a positive role in supply chain. The government should actively implement their own regulatory functions, and e-commerce platforms should also take the initiative to improve their service levels to achieve greater benefits.
Bank credit financing (RB)

In this scenario, the regulator supervises the services of the platform, and the platform bears a certain service supervision cost, while the manufacturer still obtains loans from the bank to maximize its own interest. Therefore, the profit functions are

\[ \pi^{RB}_p(s) = pq - \frac{1}{2} s^2 - h(s_0 - s) q \] (12)

\[ \pi^{RB}_m(p, e) = (1 - \rho)pq - \frac{1}{2} e^2 - r\left(\frac{1}{2} e^2 - A\right) \] (13)

**Proposition 8** Under the RB strategy, the platform’s optimal service level is

\[ s^{RB*} = \frac{(1 + r)\left[2ap(1 + r) + Bh(a - s_0)\right]}{B^2 - 2pr^2(1 + r)^2 - 2B\eta h(1 + r)} \]

The manufacturer’s optimal CER level and selling price are

\[ e^{RB*} = \frac{\lambda(1 - \rho)\left[aB - \eta h(1 + r)(a + s_0)\right]}{B^2 - 2pr^2(1 + r)^2 - 2B\eta h(1 + r)} \]

\[ p^{RB*} = \frac{(1 + r)\left[h^2(1 + r)(a + s_0)^2 - 2ahs_0B + 2a^2B^2(1 + r)\right]}{2B^2 - 4pr^2(1 + r)^2 - 4B\eta h(1 + r)} \]

\[ s^{RB*} = Ar + \frac{B(1 + r)(a - s_0)}{2\left[B^2 - 2B\eta h(1 + r) - 2pr^2(1 + r)^2\right]} \]

The optimal profits of platform and manufacturer are

\[ \pi^{RB}_p(s, \eta) = pq - \frac{1}{2} s^2 - h(s_0 - s) q - \eta \frac{1}{2} e^2 \] (14)

\[ \pi^{RB}_m(p, e) = (1 - \rho)pq - \frac{(1 - \eta) e^2}{2} \]

s.t. \( (1 - \eta) e^2 \leq A \) (15)

**Proposition 9**

(1) \( s^{RB*} > s^{RN*} \), \( p^{RB*} > p^{RN*} \), \( e^{RB*} > e^{RN*} \);

(2) \( \pi^{RB*}_m > \pi^{RN*}_m \), \( \pi^{RB*}_p > \pi^{RN*}_p \).

From Proposition 9 and Proposition 3, it can be found that the supervision of platform services by the regulator will not affect the manufacturer’s financing decisions. Bank credit will help increase the selling price and CER level and further increase the manufacturer’s profit. Moreover, the increase in profit margins of the manufacturer will increase the total commission income charged by the platform, prompting the platform to further improve its service level.

Sharing CER cost with the platform (RP)

Under the RP strategy, the platform also shares a proportion of CER costs incurred by the manufacturer. In addition, the platform needs to bear a service supervision cost when the service level is below the threshold \( s_0 \). The specific profit functions are as follows

\[ \pi^{RP}_p(s, \eta) = pq - \frac{1}{2} s^2 - h(s_0 - s) q - \frac{1}{2} \eta e^2 \] (16)

\[ \pi^{RP}_m(p, e) = (1 - \rho)pq - \frac{(1 - \eta) e^2}{2} \]

s.t. \( (1 - \eta) e^2 \leq A \) (17)

**Proposition 10** Under the RP strategy, the platform’s optimal cost-sharing ratio and service level is

\[ \eta^{RP*} = 1 - \frac{2A\left[4 - 2a(2 + g) - 4h(\eta + g + h)\right]}{4A^2} \]

\[ s^{RP*} = \frac{2a(2 + h) - h_0(2 + g + h)}{2a(2 + h) - h_0(2 + g + h)} \]

The manufacturer’s optimal CER level and selling price are

\[ e^{RP*} = \frac{a(2 + h) - h_0(2 + g + h)}{4 - 2a(2 + h) - h_0(2 + g + h)} \]

\[ p^{RP*} = \frac{a(2 + h) - h_0(2 + g + h)}{4 - 2a(2 + h) - h_0(2 + g + h)} \]

The optimal profits of platform and manufacturer are
Based on Proposition 10, the following lemma can be summarized.

**Lemma 8**

\[
\begin{align*}
\frac{\partial R_{ps}}{\partial s} &< 0; \quad \frac{\partial R_{ps}}{\partial s_iB} < 0; \\
\frac{\partial R_{ps}}{\partial h} &> 0; \quad \frac{\partial R_{ps}}{\partial h_iB} > 0. 
\end{align*}
\]

It shows that the cost-sharing ratio of the platform is also affected by service supervision. The higher the service threshold, the less willing the platform will be to share the CER cost. When the reward-penalty factor is higher, if the platform improves the service level, on one hand, it has the opportunity to obtain regulatory incentives, and it can also increase demand and further increase the profit on the other hand, so it is more willing to share cost with the manufacturer. As a result, regulators conduct service supervision on the e-commerce platform through service threshold and reward-penalty factor, which is also conducive to further cooperation between manufacturer and e-commerce platform, and eases the pressure on manufacturer to reduce carbon emissions.

**Proposition 11**

\[
\begin{align*}
\pi^R_{ps} > \pi^R_{ns}, \\
\pi^R_{m} > \pi^R_{n}.
\end{align*}
\]

Proposition 11 also indicates that service supervision on the platform will not affect the manufacturer’s financing decisions. Under service supervision, it is better for the manufacturer to choose a cost-sharing strategy with platform than to bear all CER costs itself. Through the cost-sharing strategy, the amount of funds for the manufacturer will be eased, the CER level, selling price, and service level will be improved, and profits will also be increased. Therefore, on the one hand, e-commerce platforms should actively respond to the service supervision of regulators to ensure their own service levels, and on the other hand, they should try their best to share the CER costs of manufacturers to achieve a win-win situation.

From the above analysis, whether the manufacturer chooses bank credit or share CER cost with the e-commerce platform, it can effectively solve the problem of insufficient funds. However, which financing strategy is better for the manufacturer, and whether the e-commerce platform takes the initiative to share the cost with the manufacturer, these issues are worthy to be further explored.

**Discussions and numerical analysis**

This section will further analyze the conditions for the manufacturer to choose different financing strategies and the conditions for the platform to be willing to share CER cost. Then, from a regulatory perspective, the decisions and profits of supply chain enterprises with supervision and without the supervision under the same financing strategy are compared, and policy recommendations are provided for the government.

**Comparison of different financial strategies**

According to the previous propositions, whether the manufacturer chooses financing externally or internally, it will be more appropriate than no financing. Therefore, this section further analyzes the manufacturer’s preference for bank credit and cost-sharing strategies and obtains several propositions.

**Proposition 12** Regardless of service supervision, (1) there exists \( \rho_i > 0 \) such that \( p^{iB}_s > p^{iP}_s \), \( e^{iB}_s > e^{iP}_s \) and \( \pi^{iB}_s > \pi^{iP}_s \) if \( 0 < \rho \leq \rho_i \); otherwise, \( p^{iB}_s < p^{iP}_s \), \( e^{iB}_s < e^{iP}_s \) and \( \pi^{iB}_s < \pi^{iP}_s \); (2) there exists \( \rho_i > 0 \) such that \( s^{iB}_s > s^{iP}_s \) and \( \pi^{iB}_s > \pi^{iP}_s \) if \( 0 < \rho \leq \rho_i \); otherwise, \( s^{iB}_s < s^{iP}_s \) and \( \pi^{iB}_s < \pi^{iP}_s \) (\( i = U \) or \( R \)).

It can be seen from Proposition 12 that when the commission charged by the platform is lower, the manufacturer’s selling price, CER level, and the service level provided by the platform under the bank credit strategy are higher, as well as the profits of both participants. With the increase in commission, the decisions and profits are optimal under the cost-sharing strategy, which is because the platform’s increased marginal profit makes it more willing to share CER cost with the manufacturer, resulting that the decisions under the cost-sharing strategy are better than those under the bank credit strategy. Therefore, the commission is an important factor that affects the manufacturer’s financing strategies.

Considering the complexity of the parameters, we depict an example diagram to obtain more insights. (1) From Fig. 2 a and b, although the implementation of service regulation on platform affects the manufacturer’s price and CER decisions, it will not affect the manufacturer’s financing preference. The reason is that, service supervision mainly affects...
the platform’s service level decision, while does not affect the commission. (2) The yellow area in Fig. 2 means that when the commission is low, both the platform and the manufacturer prefer the bank credit strategy; the green area means that when the commission is moderate, the platform prefers the bank credit strategy, while the manufacturer prefers cost-sharing strategy; similarly, the blue area means both the platform and the manufacturer prefer cost-sharing strategy when the commission is high. As a result, only when the commission is high enough, the platform will be willing to share the CER cost with the manufacturer. Therefore, if the commission is low, the platform is unwilling to invest, so the manufacturer should turn to bank credit financing to obtain sufficient funds for CER; if the commission is high, the platform is willing to share the cost, the manufacturer should also choose a cost-sharing strategy. Despite the higher commission, the cost-sharing strategy will yield higher benefits to the manufacturer. In addition, under the UB-UP or RB-RP hybrid strategy, the manufacturer can choose an optimal financing strategy by negotiating an appropriate commission with the platform. (3) When the platform is willing to share costs, the manufacturer’s profit under the cost-sharing strategy is also optimal. This reflects the weak bargaining power of manufacturer in the process of cooperation with the platform.

**Comparison of regulatory policies** This section analyzes the impact of service supervision on the decision-making and profits of supply chain companies and further extends the impact of service supervision on social welfare numerically. The relevant parameters are set to $\rho = 0.3$ and $r = 0.13$ (Qin et al. 2020; Xu and Fang 2020), and the values of other parameters are consistent with those in Fig. 2.

**Proposition 13**

1. $\eta^{RP^*} > \eta^{UP^*}$; (2) $s^{Rj^*} > s^{Uj^*}$, $p^{Rj^*} > p^{Uj^*}$, $e^{Rj^*} > e^{Uj^*}$; (3) $\pi^{Rj^*}_p > \pi^{Uj^*}_p$, $\pi^{Rj^*}_m > \pi^{Uj^*}_m \ (j = B$ or $P)$.

From Proposition 13(1), the proportion of CER cost shared by the platform under service supervision increases, which is understandable because service supervision urges the platform to improve service level, which leads to increased service investment cost. Therefore, the platform has an incentive to share more CER cost with the manufacturer in order to obtain more commissions. In this scenario, manufacturers should actively promote regulators to regulate e-commerce platforms, and e-commerce platforms should also actively seek cooperation with upstream and downstream enterprises to share service costs. It is obvious that the service level of the platform will increase under service supervision in Proposition 13(2). However, there are
two reasons why manufacturer’s selling price and CER level increase under service supervision. Under the RB strategy, improving the service level of the platform will increase the demand of some consumers with service preferences, which will attract the manufacturer to strengthen CER investment and increase selling price to repay bank loans. Under the RP strategy, in addition that increasing service level will stimulate demand, the platform’s increased cost-sharing ratio will also promote manufacturer’s CER investment. Therefore, regulators should observe that improving the service level of e-commerce platforms will help improve the CER level of manufacturing enterprises. There is a strong link between the two, and regulators need to guide them well.

Proposition 13 shows that the implementation of service supervision is beneficial to supply chain enterprises. Taking
(a) Manufacturer’s profits under different financing strategies when $\rho = 0.15$

(b) Manufacturer’s profits under different financing strategies when $\rho = 0.5$

(c) Platform’s profits under different financing strategies when $\rho = 0.4$

(d) Platform’s profits under different financing strategies when $\rho = 0.7$

(e) SW under different financing strategies when $\rho = 0.2$

(f) SW under different financing strategies when $\rho = 0.6$

Fig. 4 The impact of unit commission and interest rate on the profits and SW.

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cost-sharing strategy as an example, Fig. 3a and b also verifies this conclusion. Moreover, it can be found from Fig. 3c that when service threshold and reward-penalty factor satisfy certain conditions, service supervision can improve the overall social welfare. This is because service supervision ensures that the service provided by enterprises to consumers is above a certain level, and the higher the service level, not only will the enterprise be rewarded, but the utility of consumers will also be higher, which greatly improves consumer benefits. Therefore, regulators can positively promote the services provided by e-commerce enterprises by setting an appropriate service threshold and a reward-penalty factor. E-commerce platforms should also cooperate earnestly to improve services, which is of great benefit to enhancing economic interests.

Sensitivity analysis

In this section, we analyze the impact of several important parameters on the profits and social welfare. The values of parameters are consistent with those in Fig. 3.

The impact of unit commission and interest rate on profits and SW

Figure 4 describes the impact of interest rate and commission on the profits of manufacturer and platform under the different financing strategies. As the interest rate increases, both the profits under the UB and RB strategies will decrease, while profits remain unchanged under other strategies. Combining with Lemma 4, an increase in interest rate will prompt the manufacturer to reduce credit funds, leading to a reduction in investment in CER, which will reduce demand to a certain extent. The reduction in demand and selling price will weaken the profitability of manufacturer. Moreover, a reduction in the manufacturer’s marginal profit will result in a reduction in the commission charged by the platform, and thus a decline in its profit. Therefore, commission as the platform’s main source of income indicates that the manufacturer’s choice of financing strategy is also crucial to the operation of the platform.

From Fig. 4a and b, when the commission is low enough, bank credit is most beneficial to the manufacturer. As the commission increases, the platform will be more willing to share the CER cost with the manufacturer, while the profit of manufacturer is declining, which reflects the disadvantages of the manufacturer as a follower. Therefore, the manufacturer needs to carefully consider the impact of commission when making financing strategy decisions. From Fig. 4c and d, when the commission is low, the platform will be more inclined to earn dividends from the manufacturer’s bank credit strategy than to share the cost with the manufacturer. When the commission is high, the platform takes the initiative to share the cost with the manufacturer, and its own profit will increase substantially. Similarly, according to Fig. 4e and f, due to the important role of supply chain enterprises, when the commission is low, the government should support bank credit strategy for the purpose of maximizing social welfare, and when the commission is high, financing cooperation between supply chain companies should be encouraged.

Finally, it can be seen from Fig. 4 that the profits of supply chain members and social welfare under service supervision are much higher than those without supervision policy. This also shows that service supervision can not only increase economic benefits of supply chain, but is also beneficial to the social welfare, which verifies Proposition 13.

The impact of service threshold and reward-penalty factor on profits and SW

Figure 5 analyzes the impact of penalty factor and service threshold on the profits and social welfare considering service supervision policy. It can be seen that the impacts of reward-penalty factor and service threshold on platform’s profit are much greater than that on manufacturer’s profit. This is because regulators supervise the online services provided by the platform, and the platform’s decision will have an indirect impact on the manufacturer.

From Fig. 5a and b, under service supervision, regardless of the financing strategy, as the reward-penalty factor increases, the profits of the manufacturer and the platform will increase. According to Propositions 7, Lemma 7 and 8, the reason is that, an increase in the reward-penalty factor will enable the platform to vigorously improve the service level in order to avoid penalty losses, and further attract more consumers with service preferences, which is beneficial to both the manufacturer and the platform. Figure 5 e shows that the reward-penalty factor also has a positive effect on social welfare. Therefore, it can be seen that service supervision policy is of great benefit to all participants, and regulators can urge the effective implementation of service supervision by increasing penalties.

From Fig. 5c and d, as the service threshold increases, the profits of the manufacturer and the platform will decrease, but the impact on the manufacturer is not as significant as it is on the platform. It can also be seen from Propositions 7, Lemma 7 and 8 that the service threshold is negatively related to service level decision, which means that if the regulator sets the service threshold too high, it will suppress the platform’s enthusiasm for improving services. In addition, as can be seen from Fig. 5(f), overall social welfare is also negatively correlated with service threshold. Therefore, when setting service threshold, regulators should fully consider the economic benefits of the platform to avoid counterproductive effects.
(a) The impact of reward-penalty factor on manufacturer's profit

(b) The impact of reward-penalty factor on platform's profit

(c) The impact of service threshold on manufacturer's profit

(d) The impact of service threshold on platform's profit

(e) The impact of reward-penalty factor on $SW$

(f) The impact of service threshold on $SW$
Conclusions

This paper studies financing strategies of an e-commerce supply chain composed of a carbon-dependent manufacturer and a third-party platform. The manufacturer can choose to invest in CER within its own limited funds, which is considered a benchmark model, or it can choose bank credit financing or share CER costs with the platform. At the same time, the government’s supervision of service quality provided by the e-commerce platform is discussed. It is found that the CER level, price, and service under bank credit or cost-sharing with platform increase compared to the benchmark model, and the profits of manufacturer and platform also increase. Under the bank credit strategy, as the commission decreases, the manufacturer’s CER level will decline, while under the cost-sharing strategy, the CER level is positively correlated with the commission provided by the platform. Through further comparison, when the commission is low, the manufacturer obtains the highest profit under the bank credit strategy, while when the commission is high, the highest profit is obtained under the cost-sharing strategy. In addition, increasing reward-penalty factor of unit service can promote the platform to improve the service level, but an increase in the service threshold will reduce the platform’s profit.

The following management sights are summarized. First of all, it is better for manufacturers to choose financing than no financing, which is not only beneficial to supply chain companies, but also conducive to improving environmental benefits. The government can increase the CER level of enterprises by granting financial subsidies to manufacturers or encourage commercial banks to cooperate in financing with manufacturing companies that want to carry out green innovation. Secondly, whether the manufacturer chooses bank credit or shares CER cost with the platform is related to the commission provided by the platform. When the commission is low, the platform as the dominant player is unwilling to share the cost, thus it is better for the manufacturer to choose bank credit; when the commission is high, the manufacturer is more inclined to cost-sharing with the platform. For the platform, only when the commission is high enough, it will invest in the manufacturer’s CER. Therefore, in order to reach a cost-sharing agreement with the platform, the manufacturer can appropriately increase the unit commission to attract the platform and vigorously promote the low-carbon attributes of products and high-quality services to attract more consumers. The e-commerce platform should also take the initiative to help upstream manufacturing companies overcome technical challenges in CER and actively share investment costs. Finally, the government’s implementation of service supervision can indeed effectively improve the service level of the platform, but the service threshold and reward-penalty factor should not be set too high; otherwise, it will be detrimental to the overall social welfare. When formulating service supervision policies, regulators can set the service threshold appropriately low, and focus more on raising the set value of the reward-penalty factor to achieve a better urging effect. E-commerce platforms should also actively seek cooperation with upstream and downstream enterprises to improve their service levels to achieve greater benefits.

This paper also has some deficiencies to be explored in the future. For example, we study the manufacturer’s investment in CER through financing under static demand, while the influence of stochastic demand on the manufacturer’s financing decisions can be further investigated. In addition, this paper concludes that only under certain conditions can the manufacturer and platform achieve financing cooperation, so how to coordinate the two parties to make green financing strategy better is worth studying. Finally, manufacturer’s green financing under the policies of cap-and-trade and carbon tax in e-commerce supply chains is also worthy of investigating.

Appendix

Solution procedure for Proposition 1

Under the UN strategy, the Hessian matrix of $\pi_m^{UN}$ with respect to $p$ and $e$ is

$$H_m^{UN} = \begin{bmatrix} \frac{\partial^2 \pi_m^{UN}}{\partial p^2} & \frac{\partial^2 \pi_m^{UN}}{\partial p \partial e} \\ \frac{\partial^2 \pi_m^{UN}}{\partial p \partial e} & \frac{\partial^2 \pi_m^{UN}}{\partial e^2} \end{bmatrix} = \begin{bmatrix} -2(1 - \rho) \lambda(1 - \rho) & \lambda(1 - \rho) \\ \lambda(1 - \rho) & -1 \end{bmatrix}$$

where $H_m^{UN} = -2(1 - \rho) < 0$ and $\Delta(H_m^{UN}) = (1 - \rho)\left[2 - \lambda^2(1 - \rho)\right] > 0$, so $\pi_m^{UN}$ is a concave function of $p$ and $e$. Constructing the Lagrangian function

$$L(p, e, x_0) = (1 - \rho)p(a + p + \lambda \gamma + \gamma s) - \frac{1}{2}e^2 + x_0(A - \frac{1}{2}e^2)$$

where $x_0$ is a multiplier factor. Then by solving the equations

$$\frac{\partial L}{\partial p} = 0, \quad \frac{\partial L}{\partial e} = 0, \quad x_0(A - \frac{1}{2}e^2) = 0$$

we can obtain

$$e_1 = \sqrt{2A}, \quad p_1 = \frac{1}{2}(a + s\gamma + \lambda \sqrt{2A})$$

and

$$e_2 = \frac{\delta(a + s\gamma)(1 - \rho)}{2s^2(1 - \rho)} - \frac{s_2}{2}, \quad p_2 = \frac{\alpha + s\gamma}{2s(1 - \rho)}$$

Further, substituting $e_1, p_1$ and $e_2, p_2$ respectively into $\pi_p^{UN}$, and set $\frac{\partial^2 \pi_m^{UN}}{\partial p^2} = 0$,

$$s_1 = \frac{\gamma p(\alpha + \lambda \sqrt{2A})}{2 - \rho^2}, \quad s_2 = \frac{2a \gamma p}{2 - \rho^2} - \frac{2a \gamma p}{2 - \rho^2}$$

can be obtained. Meanwhile, according to the assumption $A \leq \frac{\rho e^{\sqrt{2A}}}{2(\rho e^{\sqrt{2A}})^2(1 + \gamma s)}$ and the constraint condition $\frac{1}{2}e^2 \leq A, \quad e \leq \sqrt{2A} < \frac{\delta(a + s\gamma)(1 - \rho)}{2(1 - \rho)}$, thus $\pi_m^{UN}$ is a monotonically increasing function with respect to $e$ in the range of $\left(0, \sqrt{2A}\right)$, so the set of solutions $e_2, p_2$ and $s_2$ is eliminated. Let $e^{UN} = \sqrt{2A}$ and

$$\frac{\partial^2 \pi_m^{UN}}{\partial e^2} = -1.$$
\( p^{\text{UB}} = \frac{1}{2} (a + s \gamma + \lambda \sqrt{2A}) \), and substitute \( e^{\text{UB}} \) and \( p^{\text{UB}} \) into \( \nu^{\text{UB}} \); we can get \( \frac{\partial^2 \nu^{\text{UB}}}{\partial c^2} = -(2 - \rho \gamma^2)/2 < 0, s^{\text{UB}} \), \( e^{\text{UB}} \), and \( p^{\text{UB}} \) can be obtained.

**Solution procedure for the model in Proposition 2**

Under the UB strategy, the Hessian matrix of \( \nu^m \) with respect to \( p \) and \( e \) is

\[
H_{\text{UB}} = \begin{bmatrix}
\frac{\partial^2 \phi^{\text{UB}}}{\partial p \partial e} & \frac{\partial^2 \phi^{\text{UB}}}{\partial e^2} \\
\frac{\partial^2 \phi^{\text{UB}}}{\partial p^2} & \frac{\partial^2 \phi^{\text{UB}}}{\partial p \partial e}
\end{bmatrix}
= \begin{bmatrix}
-2(1 - \rho) \lambda(1 - \rho) \\
\lambda(1 - \rho) - 1 - \eta
\end{bmatrix}
\]

where \( H_{\text{UB}} = \begin{bmatrix} \nu_{\text{UB}}^{(1,1)} \end{bmatrix} = -(2 - \rho \gamma^2)/2 < 0 \) and \( \Delta(H_{\text{UB}}) = (1 - \rho) [2(1 + \rho) - \lambda^2(1 - \rho)]^2 > 0 \), so \( e^{\text{UB}} \) is a concave function of \( p \) and \( e \). Unique \( \nu^{\text{UB}} \) and \( p^{\text{UB}} \) can be obtained, and substitute them into \( \nu^{\text{UB}} \), we can get \( \frac{\partial^2 \nu^{\text{UB}}}{\partial c^2} = -1 + \frac{2(1 + \rho) - \lambda^2(1 - \rho)}{[2 + 2\rho(1 - \rho)/(1 + \rho)]^2}, \) because \( 0 < \rho, \gamma < 1, \rho > 0 \), we can deduce \([2 + 2\rho(1 - \rho)/(1 + \rho)] \leq [2 + 2\rho(1 - \rho)] > 0 \), thus \( \frac{\partial^2 \nu^{\text{UB}}}{\partial c^2} < 0 \). There is a unique \( \nu^{\text{UB}} \).

**Proof of Proposition 3**

Because \( A < \sqrt{2A} \), we have \( e(U^B) > e(U^{UN}) \). Because \( s_{UN} = \frac{\gamma \rho [(e + \Delta \nu^{\text{UB}})/(2B - 2\rho \gamma^2 + B^2)] - \frac{\gamma \rho [(e + \Delta \nu^{\text{UB}})/(2B - 2\rho \gamma^2 + B^2)]}{(2B - 2\rho \gamma^2 + B^2)} \), there is a unique \( e(U^B) = e(U^{UN}) \) for \( B = 2 + 2\rho(1 + \rho) > 0 \).

**Solution procedure for the model in Proposition 4**

Under the UP strategy, the Hessian matrix of \( \nu^p \) with respect to \( p \) and \( e \) is

\[
H_{\text{UP}} = \begin{bmatrix}
\frac{\partial^2 \phi^{\text{UP}}}{\partial p \partial e} & \frac{\partial^2 \phi^{\text{UP}}}{\partial e^2} \\
\frac{\partial^2 \phi^{\text{UP}}}{\partial p^2} & \frac{\partial^2 \phi^{\text{UP}}}{\partial p \partial e}
\end{bmatrix}
= \begin{bmatrix}
-2(1 - \rho) \lambda(1 - \rho) \\
\lambda(1 - \rho) - 1 + \eta
\end{bmatrix}
\]

where \( H_{\text{UP}} = \begin{bmatrix} \nu_{\text{UP}}^{(1,1)} \end{bmatrix} = -(2 - \rho \gamma^2)/2 < 0 \) and \( \Delta(H_{\text{UP}}) = (1 - \rho) [2(1 + \rho) - \lambda^2(1 - \rho)]^2 > 0 \). Similar to Proposition 1, according to the assumption \( A < \sqrt{2B^2 \lambda^2(1 - \rho)/(2B - 2\rho \gamma^2 + B^2)} \), it can be seen that \( \nu^{\text{UP}} \) is a monotonically increasing function with respect to \( e \) in the range of \( 0, \sqrt{2A} \). That is, \( e^* = \sqrt{2A}/(1 - \eta) \), and \( p^{\text{UP}} \) can be obtained. Substituting \( e^* \) and \( p^{\text{UP}} \) into \( \nu^{\text{UP}} \), we can get \( \nu^{\text{UP}} = -(2 - \rho \gamma^2)/2 < 0 \) and \( \Delta(H^{\text{UP}}) = \lambda^2 \gamma^2 + (1 - \rho^2) (\gamma^2/2 - 4\rho(1 - \rho)^2) > 0 \), thus there is a unique \( \eta^{\text{UP}} \) and \( s^{\text{UP}} \).

**Proof of Proposition 5**

(1) For the convenience of comparison, we take \( 0 \leq \eta < 1 \) as an exogenous variable, and the optimal decisions under UP strategy is \( e^{\text{UP}} = \sqrt{\frac{2A}{1 - \eta}} \), \( p^{\text{UP}} = \frac{\alpha + \lambda \sqrt{\frac{2A}{1 - \eta}}}{2 - \rho \gamma^2}, \)

\( s_{UP} = \frac{\gamma \rho [(e + \Delta \nu^{\text{UP}})/(2B - 2\rho \gamma^2 + B^2)]}{(2B - 2\rho \gamma^2 + B^2)} \).

Since \( e^{\text{UP}} = \sqrt{\frac{2A}{1 - \eta}} > e_{\text{UN}} = \sqrt{2A} \), \( p^{\text{UP}} > p_{\text{UN}} \) and \( s^{\text{UP}} > s_{\text{UN}} \) can be obtained.

When \( \eta \) is an exogenous variable, \( \nu^{\text{UP}} = \\frac{\rho [(e + \Delta \nu^{\text{UP}})/(2B - 2\rho \gamma^2 + B^2)]}{(2B - 2\rho \gamma^2 + B^2)} \), \( \nu^{\text{UP}} = \frac{\rho [(e + \Delta \nu^{\text{UP}})/(2B - 2\rho \gamma^2 + B^2)]}{(2B - 2\rho \gamma^2 + B^2)} - A \). Owing to \( \nu^{\text{UN}} = \nu_{\text{UN}} = \frac{\rho [(e + \Delta \nu^{\text{UN}})/(2B - 2\rho \gamma^2 + B^2)]}{(2B - 2\rho \gamma^2 + B^2)} > 0 \), \( \nu_{\text{UP}} - \nu^{\text{UN}} > 0 \), \( \nu_{\text{UP}} > \nu^{\text{UN}} > 0 \), thus \( \nu_{\text{UP}} > \nu^{\text{UN}} \), \( \nu_{\text{UP}} > \nu_{\text{UN}} \).
Solution procedure for the model in Proposition 6

Substituting the values of \( \tilde{e}^{UN} \) and \( \tilde{p}^{UN} \) in Proposition 1 into \( \pi^{RN} \), owing to \( 0 < \rho < 1 \), \( \gamma < 1 \), we can get \( \partial^{2} \pi^{RN} / \partial s^{2} = - (2 - \rho^{2} \gamma - 2 \rho \gamma) / 2 < 0 \), so \( \pi^{RN} \) is a concave function of the service level \( s \). The unique \( s^{RN*}, e^{RN*} \) and \( p^{RN*} \) can be obtained.

Proof of Proposition 7

(1) \( \partial s^{RN} / \partial s_{0} = \frac{h_{s}}{2(2-h_{s}-\gamma_{s})} < 0 \), \( \partial \rho^{RN} / \partial s_{0} = - \frac{h_{s}^{2}}{2(2-h_{s}-\gamma_{s})} < 0 \), \( \partial s^{RN} / \partial h_{s} = \frac{h_{s}^{2}}{(2-h_{s}-\gamma_{s})} > 0 \), \( \partial \rho^{RN} / \partial h_{s} = \frac{h_{s}^{2}}{(2-h_{s}-\gamma_{s})} > 0 \).

(2) \( \omega \) that \( e^{RN*} - e^{UN*} = 0 \), \( s^{RN*} - s^{UN*} = \frac{h^{*}}{(2-h_{s}-\gamma_{s})} \) \( > 0 \), \( p^{RN*} - p^{UN*} = \frac{h^{*}}{(2-h_{s}-\gamma_{s})} \) \( > 0 \), thus \( e^{RN*} > e^{UN*} \) \( s^{RN*} > s^{UN*} \), \( p^{RN*} > p^{UN*} \).

(3) \( \omega \) the difference \( \pi^{RN*} - \pi^{UN*} = \left[ \left( 1 - \rho^{*} \right) \left( 2 - \rho^{*} \gamma_{s} \right) \right] > 0 \), \( \therefore \pi^{RN*} > \pi^{UN*} \). \( \therefore \pi^{RN*} = (1 - \rho)p^{RN*} + q^{RN*}p^{RN*} - \frac{1}{2}e^{RN*}^{2} \), \( \pi^{UN*} = (1 - \rho)p^{UN*} + q^{UN*}p^{UN*} - \frac{1}{2}e^{UN*}^{2} \). Therefore, \( p^{RN*} > p^{UN*} \), \( q^{RN*} > q^{UN*} \), \( e^{RN*} > e^{UN*} \), we can obtain \( \pi^{RN*} > \pi^{UN*} \).

Solution procedure for the model in Proposition 8

Substituting the values of \( \tilde{e}^{UB} \) and \( \tilde{p}^{UB} \) in Proposition 2 into \( p^{UB} \), we can get \( \partial^{2} \pi^{RB} / \partial s^{2} = - \left( B^{2} - 2 \rho^{2} \gamma^{2} (1 + r) - 2Bh_{s} (1 + r) \right) / B^{2} \), because \( 0 < \rho < 1 \), \( \gamma < 1 \), \( r > 0 \), we can deduce \( B^{2} - 2 \rho^{2} \gamma^{2} (1 + r) - 2Bh_{s} (1 + r) > B^{2} - 2 (1 + r)^{2} - 2Bh_{s} (1 + r) = 2 (1 + r)^{2} (1 - 2h_{s}) + 2 \rho^{2} (1 + r) (1 - \rho) / 2 - h_{s}^{2} - 2h_{s} (1 - \rho) \), thus \( \partial^{2} \pi^{RB} / \partial s^{2} < 0 \). Equilibria \( s^{RB*}, e^{RB*} \) and \( p^{RB*} \) can be obtained.

Proof of Lemma 7

(1) Because \( A \leq \frac{\alpha^{2} B^{2} \gamma^{2} (1 - \rho^{2})}{2} \), we can get \( \pi^{RB*} = \frac{\alpha^{2} B^{2} \gamma^{2} (1 - \rho^{2})}{2} \), and the difference \( \pi^{RB*} > \pi^{RN*} \); \( \therefore s^{RB*} > s^{RN*} \). \( \therefore \pi^{RB*} > \pi^{RN*} \), through calculation, \( \pi^{RB*} = \frac{\alpha^{2} B^{2} \gamma^{2} (1 - \rho^{2})}{2} > \pi^{RN*} \), \( \therefore s^{RB*} > s^{RN*} \).

(2) Given \( \sqrt{2A} > \rho^{RB*} \), \( \pi^{RB*} = (1 + r) \left[ \frac{\alpha^{2} B^{2} \gamma^{2} (1 - \rho^{2})}{2} - 2h_{s} (1 + r) \right] / (1 + r) \), \( \pi^{RB*} = \frac{8 - \rho^{2} \gamma^{2}}{8 - \rho^{2} \gamma^{2}} \), we can know the difference \( \pi^{RB*} - \pi^{RN*} = \frac{\alpha^{2} B^{2} \gamma^{2} (1 - \rho^{2})}{2} \left[ (1 + r) \left( 2 - \rho^{2} \gamma^{2} / A \right) - 2 \rho^{2} \gamma^{2} / A \right] > 0 \), \( \therefore \pi^{RB*} > \pi^{RN*} \). Therefore, \( \pi^{RB*} > \pi^{RN*} \). The conclusion \( \pi^{RB*} > \pi^{RN*} \) is proved.

Given \( \pi^{RB*} = \frac{\alpha^{2} B^{2} \gamma^{2} (1 - \rho^{2})}{2} \), \( \pi^{RN*} = \alpha^{2} B^{2} \gamma^{2} (1 - \rho^{2}) / A \), we can deduce \( \rho_{0}^{RB*} < 1 \).

\( \Phi > \frac{\alpha^{2} B^{2} \gamma^{2} (1 - \rho^{2})}{2} \left( 2 - \rho^{2} \gamma^{2} / A \right) > 0 \), thus \( \Phi > 0 \). This \( \pi^{RB*} > \pi^{RN*} \) is proved.
Solution procedure for the model in Proposition 10

Substituting the values of $e^{UP}$ and $p^{UP}$ in Proposition 4 into $\pi^{RP}_p$, we can get $H'_p^{RP} = \{-1 - h_y - \frac{\pi^2}{2}\} < 0$, and $H'_2^{RP} = -\frac{8(2 - \pi^2) - 3\hat{A}(\hat{A} - \pi^2)\sqrt{v(\pi - 1)}}{8\pi^2} < 0$, because the solution process is similar to that of Proposition 4, there is a unique $\eta^{RP}$ and $s^{RP}$.

Proof of Proposition 11

(1) For the convenience of comparison, we take $0 \leq \eta < 1$ as an exogenous variable, and the optimal decisions under RP strategy is $e^{RP} = \sqrt{\frac{2A}{1 - \eta}}$, $p^{RP} = \frac{(a + \sqrt{\frac{2A}{1 - \eta}})(2 - \pi^2) - \tau^2}{2(2 - \pi^2 - 2h^2)}$, $s^{RP} = \frac{(a + \sqrt{\frac{2A}{1 - \eta}})(2 - \pi^2) - \tau^2}{2(2 - \pi^2 - 2h^2)}$. Since $e^{RP} > e^{RN} = \sqrt{2A}$, $p^{RP} > p^{RN}$ and $s^{RP} > s^{RN}$ can be obtained.

When $\eta$ is an exogenous variable, the optimal profits

$$s^{RP} = \frac{(a + \sqrt{\frac{2A}{1 - \eta}})(2 - \pi^2) - \tau^2}{2(2 - \pi^2 - 2h^2)} - A \cdot \phi^{RP}$$

and

$$\pi^{RP}_m = \frac{(a + \sqrt{\frac{2A}{1 - \eta}})(2 - \pi^2) - \tau^2}{2(2 - \pi^2 - 2h^2)} - A \cdot \phi^{RP}$$

Thus, $\phi^{RP} > \phi^{RN}$, apparently $\sqrt{\frac{2A}{1 - \eta}} > \sqrt{2A}$, thus

$$\phi^{RP} > \phi^{RN}$$

Proof of Proposition 12

Without service supervision, given $p^{UB} = \frac{aB + (a + b)B}{B^2 - 2B(1 + d)\rho}$, $p^{UP} = \frac{aB}{2 - (1 + d)^2 \rho}$, assuming $p^{UB} = p^{UP}$, we can get

$$\rho_1 = \rho_1 = \frac{1}{\sqrt{(1 + d)^2 + 2(1 + d)\rho^2}}$$

(1 reject), where $\Gamma_1 = -4 + (1 + \tau)^2 + (3 + \tau)(\tau^2 - 2\tau)$, $\Gamma_2 = (1 + \tau)(\sqrt{\tau^2 + 1} + 8(2 - \pi^2) + 4(4 - \pi^2 - \pi^2) + \pi^2 + \tau^2)^2$, and further simplifying the inequality $p^{UB} > p^{UP} > 0$ can get $\rho > \rho_1$. On the contrary, $p^{UB} < p^{UP}$ when $\rho < \rho_2$.

(1) Given $\lambda^{UB} = \frac{aB + (a + b)B}{B^2 - 2B(1 + d)\rho}$, $\lambda^{UP} = \frac{aB}{2 - (1 + d)^2 \rho}$, assuming $\lambda^{UB} = \lambda^{UP}$, we can get

$$\rho_2 = \rho_2 = \frac{aB}{\sqrt{aB - 2B(1 + d)(1 + d)\rho}} < 0 (\text{reject}),$$

and further simplifying the inequality $\lambda^{UB} > \lambda^{UP}$ we can get $\rho < \rho_2$. On the contrary, $\lambda^{UB} < \lambda^{UP}$ when $\rho > \rho_2$. Similarly, assuming that $p^{UB} = p^{UP}$, $p^{UB} = p^{UP}$ and $\pi^{UB} > \pi^{UP}$, the critical value of $\rho$ can be obtained, which will not be repeated here, and the same is true under service supervision.

Proof of Proposition 13

Given

$$\eta^{RP} = 1 - \frac{2A}{\sqrt{aB + (a + b)B}}$$

and

$$\eta^{UP} = 1 - \frac{2A}{\sqrt{aB + (a + b)B}}$$

we assume

$$\Phi^1 = \frac{2A}{\sqrt{aB + (a + b)B}}$$

and

$$\Phi^2 = \frac{2A}{\sqrt{aB + (a + b)B}}$$

Then

$$\eta^{RP} - \eta^{UP} = \Phi^2 - \Phi^1 = (\Phi^1 - \Phi^1) + (\Phi^1 - \Phi^1)$$

Because

$$\Phi^2 - \Phi^1 = \frac{aB[2(2 - \pi^2)B] - h_0(2 - \pi^2)B > 0, \text{ thus }} \eta^{RP} > \eta^{UP}$$

According to the difference

$$s^{RP} - s^{UP} = \frac{aB[2(2 - \pi^2)B] - h_0(2 - \pi^2)B > 0}$$

and

$$e^{RP} - e^{UP} = \frac{aB[2(2 - \pi^2)B] - h_0(2 - \pi^2)B > 0}$$

We can obtain the comparison between RB and UB strategies is similar and will not be repeated here.

According to the difference

$$\pi^{RP}_m - \pi^{UP}_m = \frac{\{aB[2(2 - \pi^2)B] - h_0(2 - \pi^2)B > 0\}}{4(2 - \pi^2 + \pi^2)}$$

Thus

$$\pi^{RP}_m > \pi^{UP}_m.$$
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