OPTIMAL FINANCING AND OPERATIONAL DECISIONS OF CAPITAL-CONSTRAINED MANUFACTURER UNDER GREEN CREDIT AND SUBSIDY

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ABSTRACT. To stimulate the capital-constrained manufacturer to produce green products, the government often adopts two incentive mechanisms: green credit (i.e., subsidy offered directly to bank) and subsidy (i.e., subsidy offered directly to manufacturer). This paper examines the optimal interest rate of the bank, and the optimal product green degree and sales price of the manufacturer under the two mechanisms, respectively. Furthermore, we investigate the effects of these mechanisms on the optimal decisions, the profits of players, the social welfare and the environmental benefits. Several important results are obtained. First, when the total government subsidy is low, the green credit mechanism can bring the higher green degree, product sales price and demand, as well as higher profits for the bank and manufacturer, rather than the subsidy mechanism. Otherwise, the result is opposite. Second, the government should adopt the green credit mechanism to support the manufacturer to develop green products when the budget is limited and relatively low. If the government budget is sufficient, the subsidy mechanism is the best choice, which can bring higher economic and environmental benefits.

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1. **Introduction.** In order to reduce the environmental pollution caused by the manufacturing industry and improve the ecological environment, many governments guide and encourage enterprises to produce green products and develop green economy [16, 26]. However, at the beginning of the development of such green products, since the initial R&D costs and investment costs of production equipments are very high, and the market share of the green products is relatively low, many companies are encountering with problems of funding shortage [20, 27]. Therefore, many governments have launched a few targeted incentives to directly or indirectly support the production of green products for enterprises [13]. For example, some national governments provide subsidies for enterprises that produce energy-efficient appliances [9, 32]. At present, electric vehicles are a classic example. Many enterprises have successfully developed and produced electric vehicles, such as Tesla in the United States, Nissan in Japan, and BMW in Germany [9]. In addition, electric vehicles are expected to replace gasoline vehicles in the future, as their non-carbon dioxide emissions are much lower or even zero. To promote the development of electric vehicles, the U.S. government offered $2500 to $7500 tax credit to consumers who bought electric vehicles in 2010. Since 2011, the UK government has provided a 25% price discount rate to each electric vehicle buyer [9].

In general, governments usually adopt two kinds of incentive mechanisms to directly or indirectly subsidy green manufacturers. One is green credit mechanism, under which the government provides banks with finance discount, and urges them to offer low-interest financing services to the green product manufacturers [1, 20]. It is a new type of government subsidy in recent years. For example, the German government provides subsidies to banks and urges them to offer low-interest loans (2.5% to 5.1%) for wind and photovoltaic projects [33]. The other is subsidy mechanism [32], under which the government provides price subsidy to manufacturers directly. For example, the Chinese government provides a price subsidy of RMB 15,000 to RMB 50,000 per electric vehicle to customers who buy new energy vehicles in 2018.

It should be noted that the development of green products involves many issues such as the government incentive mechanism, financing, production and sales; regarding the capital-constrained green manufacturer, it is necessary to examine the effects of different incentive mechanisms on the financing and operational decisions of the bank and manufacturer, as well as social welfare and environmental benefits. Therefore, some research issues are naturally raised in this study:

1) How to determine the optimal interest rate of the bank, the optimal green degree and sales price of the capital-constrained manufacturer under the two mechanisms of green credit and subsidy?

2) How do different government incentive mechanisms affect the optimal operational decisions and the profits of the bank and the capital-constrained manufacturer, as well as the social welfare and environmental benefits?

Obviously, through studying the above issues and conducting relevant theoretical analysis, some valuable conclusions and important management implications can be obtained to improve the decision qualities of the government and bank, as well as the operation management of the capital-constrained green manufacturer.

The main purpose of this paper is to focus on the effects of green credit and subsidy mechanisms on green product design and pricing decision of the capital-constrained manufacturer. In this study, a financial supply chain that consists.

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1 [http://jjs.mof.gov.cn/zhengwuxinxi/zhengcefagui/201802/t201802132815574.html](http://jjs.mof.gov.cn/zhengwuxinxi/zhengcefagui/201802/t201802132815574.html)
of a bank and a capital-constrained green manufacturer is proposed. Considering
that the government adopts green credit mechanism and subsidy mechanism, an
optimization model is established with the aim of maximizing the profits of the
bank and the manufacturer. Through solving the model, the optimal interest rate of
the bank, the optimal sales price and the optimal green degree of the manufacturer
can be obtained under each mechanism, respectively. Further, we compare the
operational decisions and profits of the bank and the manufacturer under the two
mechanisms, and we also analyze the effects of the two mechanisms on the social
welfare and environmental benefits.

The remainder of this paper is organized as follows. In Section 2, we briefly
review the related literature. Section 3 describes the problem and puts forward
the notations and assumptions of the basic model. Section 4 gives the optimal
decisions of the bank and the manufacturer, and related analyses under green credit
and subsidy are presented. In Section 5, we comparatively analyze the optimal
decisions and profits of the bank and the manufacturer under two mechanisms, as
well as the social welfare and the environmental benefits. Section 6 gives a series
of numerical examples to analyze and verify some results. Section 7 gives an extended
analysis. Section 8 summarizes the main conclusions and suggests future research
perspectives.

2. Literature review. This work is closely related to the existing literatures in two
aspects: the operational decisions of capital-constrained supply chain, in addition
to the supply chain operational decisions and government policy in the context of
green product production. The relevant literatures are reviewed as below.

2.1. Operational and financing decisions of capital-constrained supply
chain. In one of the pioneering studies, Che and Gale [8] found that if the firms in
the supply chain are capital constraint, it will influence the normal operation of the
supply chain. Subsequently, many scholars begin to pay attention to the problems
of financing and operational decisions in the capital-constrained supply chain and
thus many relevant research literatures are constantly emerging [4, 7, 14, 22, 23, 31].

Buzacott and Zhang [5] pioneered in studying the integration of supply chain
logistics and capital flows and obtain the optimal inventory decision of the capital-
constrained manufacturer and the optimal financing decision of the bank under
bank financing mode in the uncertain market. Kouvelis and Zhao [17] considered
the factor of bankruptcy cost in the process of capital-constrained supply chain
operation, and analyzed the impact of bankruptcy cost on the optimal ordering
and financing decisions of the capital-constrained company. Jing et al. [15] studied
the optimal operational decisions of the supply chain under trade credit and bank
financing respectively. They noted that the supplier will give a lower wholesales
price under trade credit than that under bank financing, which can encourage the
retailer to choose the former. Kouvelis and Zhao [18] studied the coordination prob-
lem of capital-constrained supply chain considering bankruptcy cost, and obtained
the revenue-sharing contract that can achieve supply chain coordination. Yang et
al. [34] considered a two-echelon supply chain composed of one supplier and two
capital-constrained retailers, and examined the effect of equilibrium financing on the
decisions of supply chain participants and the performance of supply chain. Wang
et al. [29] considered three common mechanisms that suppliers use to address the.credit default problems including screening, checking and insurance. In addition,
they studied trade credit contracting under asymmetric credit default risk. Wu et
al. [30] examined a green supply chain consisting of a manufacturer and a capital-constrained retailer. They studied the optimal decision and coordination of supply chain under bank financing and trade credit.

2.2. Operational decisions and government policy of green supply chain. In recent years, the research on operational decisions of green supply chain has attracted the attentions from many scholars [10, 11, 27]. Tseng and Hung [28] studied the production and operational decisions of green supply chain considering the social cost of carbon emission. Zhang et al. [35] proposed the optimal decisions of supply chain that consists of a manufacturer and a retailer under three modes, namely the centralized mode, decentralized mode, and coordination mode based on the buyback contract. In additions, they focused on the impact of consumer environmental awareness on the supply chain operational and coordination decisions. Zhu and He [36] analyzed the impacts of green supply chain structures, green product types, and green product competition forms on product green degree and production decisions. Song and Gao [25] designed two revenue-sharing contracts that can achieve green supply chain coordination.

Moreover, some scholars focus on the impact of government incentive mechanism on the operational decisions in green supply chain management [2, 12, 21, 24]. For example, regarding that the government provides subsidy for consumers, Cohen et al. [9] studied the impact of uncertain market demand on the design and government decisions of green supply chain. Yang and Xiao [32] studied the green supply chain pricing decision and green degree level design with government interventions under fuzzy uncertainties. Bi et al. [3] studied the green product production decisions of two manufacturers and the government subsidy decision under two situations (i.e., one is that the government’s budget is limited and the other is that the government’s budget is sufficient).

From the above mentioned researches, it can be seen that the related literatures have made significant contributions to the studies of operational decisions of capital-constrained supply chain and the government subsidy decisions of green supply chain. Some valuable conclusions and management implications have been drawn. However, with regard to the operational decisions of capital-constrained supply chain, the existing literatures mainly focused on supply chain with general product rather than green product. Besides, with regard to government incentive mechanism of green supply chain, most of the existing studies did not concern green credit mechanism and the manufacturer’s insufficient funding situation. Though Yang et al. [33] examined the value of green financial policies and production subsidy under the condition of capital constraints, they did not consider green product design and government budget issues. To fill this research gap, this paper studied the optimal decisions of the capital-constrained green manufacturer and the bank under the mechanisms of green credit and subsidy. Furthermore, we also analyze the two mechanisms under different government budgets, which differ from those of Yang et al. [33].

This study contributes to the existing literature in two aspects. Firstly, this paper considers a capital-constrained green manufacturer and studies the green operational decisions under two mechanisms, which differs from the existing researches. Especially, we focus on the study of green credit, which is a new incentive mechanism and often ignored in existing researches. Secondly, through theoretical analysis, we can obtain the specific conditions of the government’s decision-making and budget. Therefore, we can provide some practical and instructive managerial
implications for the decisions of the bank, the capital-constrained manufacturer and the government.

3. **Notations and assumptions.** In this paper, we assume that the manufacturer is subject to capital constraint when it invests in green technology to produce green products, and the bank would like to offer financing service for the manufacturer. After the green products are produced and sold to the consumers, the manufacturer repays the loan principal and interest to the bank. The bank and the manufacturer follow the Stackelberg game, led by the bank and followed by the manufacturer. The specific decision-making sequences are that the bank first determines the interest rate, and the manufacturer then decides the sales price and green degree of the product.

Two government incentive mechanisms are considered. One is the green credit mechanism, namely the government provides finance discount to the bank and urges the bank to provide low-interest green credit to the manufacturer, as shown in Figure 1; the other is the subsidy mechanism, that is the government provides price subsidy to the manufacturer, at the meanwhile, the bank provides financing service to the manufacturer, as shown in Figure 2.

**Figure 1.** The green credit mechanism

**Figure 2.** The subsidy mechanism

For the ease of expression, the symbols to be used in this study are defined as below:
- $p_i$: The unit sales price of the manufacturer (decision variable);
- $e_i$: The green degree of the unit product (decision variable), $e_i > 0$;
- $r_i$: The interest rate of the bank (decision variable);
- $\tau_i$: The subsidy rate of the government, $\tau_i > 0$;
- $k$: The cost factor of the manufacturer for green technology investment, $k \geq 1$;
- $\theta$: The green preference coefficient of the customers, $0 < \theta \leq 1$;
- $B_i$: The total subsidy of the government, $B_i > 0$.

Moreover, let $i = 0$ denotes the scenario that the government does not provide any subsidy, $i = 1$ denotes green credit mechanism, $i = 2$ denotes subsidy mechanism. We assume that the market demand is modeled as $d_i = a - p_i + \theta e_i$ [36], where $a > 0$. The constant $a$ indicates the potential market size of the green product. The higher the green degree (such as the driving distance of electric cars), the greater the demand. We further assume that the manufacturer’s funding gap (its initial capital is subtracted) is related to the investment cost of green technology, namely the manufacturer’s funding gap can be expressed as $\frac{1}{2}ke^2$ [19]. In addition,
this paper takes the intensive-development green product as the research object, assuming that the marginal production cost can be negligible [36]. Without loss of generality, we assume the market is completely competitive, that is the risk-free interest rate of market is zero. We also regard the bank and the manufacturer as risk-neutral and completely rational, respectively. Besides, the interest rate of the bank under green credit is assumed to be smaller than that without the government subsidy, i.e., \( r_1 < r_0 \).

4. Optimal decisions of the bank and the manufacturer under two mechanisms. We study the optimal decisions of the bank and the manufacturer under two mechanisms, respectively.

4.1. Optimal decisions of the players under green credit. Under green credit mechanism, the government provides finance discount to the bank at a rate \( \tau_1 \) and urges the bank to offer a \( \frac{1}{2} k e_1^2 \) loan to the capital-constrained manufacturer at a lower interest rate \( r_1 \), in order to ensure normal production of the manufacturer. At the end of the sales season, the manufacturer can obtain a revenue \( p_1 d_1 \) and needs to repay the principal and interest \( \frac{1}{2} k e_1^2 (1 + r_1) \) to the bank. The profit functions of the bank and manufacturer can be written in Equations (1) and (2):

\[
\Pi^B_1(r_1) = \frac{1}{2} k e_1^2 (\tau_1 + r_1),
\]

\[
\Pi^M_1(p_1, e_1) = p_1 d_1 - \frac{1}{2} k e_1^2 (1 + r_1),
\]

We adopt the converse-solving method to solve Equations (1) and (2) in turn. Thus, we can obtain the following proposition.

**Proposition 1.** Under green credit mechanism, the bank’s optimal interest rate is \( r_1^* = \frac{2k - \theta^2 - 4k \tau_1}{2k} \), the optimal product green degree of the manufacturer is \( e_1^* = \frac{a \theta}{4k - 2 \theta^2 - 4k \tau_1} \), and the optimal sales price is \( p_1^* = \frac{a(4k - \theta^2 - 4k \tau_1)}{8k - 4 \theta^2 - 8k \tau_1} \).

The proof of Proposition 1 is detailed in Appendix 1.

According to Proposition 1, the market demand of the product is \( d_1^* = \frac{a(4k - \theta^2 - 4k \tau_1)}{8k - 4 \theta^2 - 8k \tau_1} \). And the total subsidy of government is

\[
B_1 = \frac{1}{2} k e_1^2 \tau_1,
\]

In the light of Proposition 1, the following corollaries can be obtained.

**Corollary 1.** Under green credit mechanism, we have \( \frac{\partial r_1^*}{\partial \tau_1} < 0 \), \( \frac{\partial e_1^*}{\partial \tau_1} > 0 \), \( \frac{\partial p_1^*}{\partial \tau_1} > 0 \), \( \frac{\partial d_1^*}{\partial \tau_1} > 0 \), \( \frac{\partial \Pi^B_1}{\partial \tau_1} > 0 \), \( \frac{\partial \Pi^M_1}{\partial \tau_1} > 0 \), and \( \frac{\partial \Pi^M_1}{\partial \theta} > 0 \).

The proof of Corollary 1 is detailed in Appendix 2.

Corollary 1 shows that when the government provides discount interest subsidy to the bank, with the increase of government’s subsidy, the bank’s interest rate can be decreased. In doing so, the financing cost of the manufacturer can be reduced, and the product green degree of the manufacturer can be improved. Accordingly, the sales price will be higher and the market demand will be larger; thus the bank and the manufacturer can both gain more profits.

**Corollary 2.** Under green credit mechanism, we have \( \frac{\partial r_1^*}{\partial \theta} < 0 \), \( \frac{\partial e_1^*}{\partial \theta} > 0 \), \( \frac{\partial p_1^*}{\partial \theta} > 0 \), \( \frac{\partial d_1^*}{\partial \theta} > 0 \), \( \frac{\partial \Pi^B_1}{\partial \theta} > 0 \), \( \frac{\partial \Pi^M_1}{\partial \theta} > 0 \), and \( \frac{\partial \Pi^M_1}{\partial \theta} > 0 \).
The proof of Corollary 2 is detailed in Appendix 3.

Corollary 2 shows under the green credit mechanism, the greater the green preference coefficient of the customers is, the more consumers would like to prefer green product, which means that the market demand of the green product becomes larger. Then the manufacturer will determine higher green degree and sales price of the green product, as well as the bank will reduce the interest rate. Thus the bank and the manufacturer can both gain more profits.

4.2. Optimal decisions of the players under green credit. Under the subsidy mechanism, the government provides price subsidy for the manufacturer at the subsidy rate $\tau_2$, and the bank offers loans $\frac{1}{2}ke_2^2$ for the manufacturer at a interest rate $r_2$. At the end of the sales season, the manufacturer can obtain revenue $p_2d_2$ and needs to repay the loan principal and interest $\frac{1}{2}ke_2^2(1 + r_2)$ to the bank. The profit functions of the bank and the manufacturer can be written as follows:

$$\Pi_B^2(r_2) = \frac{1}{2}ke_2^2r_2,$$

$$\Pi_M^2(p_2, e_2) = p_2(1 + \tau_2)d_2 - \frac{1}{2}ke_2^2(1 + r_2).$$

We adopt the converse-solving method to solve Equations (4) and (5) in turn. Thus, we can obtain the following proposition.

**Proposition 2.** Under subsidy mechanism, the bank’s optimal interest rate is $r^*_2 = \frac{2k-\theta^2(1+\tau_2)}{2k}$, the optimal product green degree of the manufacturer is $e^*_2 = \frac{a\theta(1+\tau_2)}{4k-4\theta^2(1+\tau_2)}$, and the optimal sales price is $p^*_2 = \frac{a[4k-\theta^2(1+\tau_2)]}{8k-4\theta^2(1+\tau_2)}$.

The proof of Proposition 2 is detailed in Appendix 4.

According to Proposition 2, the market demand of the product is $d^*_2 = \frac{a[4k-\theta^2(1+\tau_2)]}{8k-4\theta^2(1+\tau_2)}$. And the total subsidy of the government is

$$B_2 = p^*_2d^*_2\tau^*_2,$$

5. Comparative analysis between two mechanisms. For the comparative analysis about the effects of green credit and subsidy on the supply chain performance, it is indispensable to know the optimal decisions of the players when the government does not provide any subsidy. Under this circumstance, assuming that $\tau_0 = 0$, it is easy to obtain the bank’s optimal interest rate $r^*_0 = \frac{2k-\theta^2}{2k}$, the optimal product green degree of the manufacturer $e^*_0 = \frac{a\theta}{4k-2\theta^2}$, the optimal sales price $p^*_0 = \frac{a[4k-\theta^2]}{8k-4\theta^2}$, and the market demand $d^*_0 = \frac{a[4k-\theta^2]}{8k-4\theta^2}$, respectively.

From Propositions 1, 2 and the above analysis, we can see that the optimal decisions of the bank and the green product manufacturer under three scenarios (i.e., green credit, subsidy, and non-subsidy) are quite different. In this section, considering that the total government subsidy under two mechanisms is equal, we analyze the effects of these two mechanisms on the optimal decisions and profits of the bank and the manufacturer, in addition to the consumer surplus, the social welfare and the environmental benefits.

5.1. The optimal decisions and profits of the bank and the manufacturer. These following propositions can be concluded by comparing the optimal decisions of the bank and the manufacturer under three scenarios.
Let $\Delta r_1$ and $\Delta r_2$ indicate the range of interest rate cut under two mechanisms (refer to the interest rate of the bank without any subsidy as a reference point for other scenarios), then $\Delta r_1 = r_0^* - r_1^* = 2r_1$ and $\Delta r_2 = r_0^* - r_2^* = \frac{\theta^2}{2k}r_2$.

**Proposition 3.** When $B_1 = B_2$, 1) it holds that $\Delta r_1 > \Delta r_2$; 2) if $0 < B_i < \frac{a^2\theta^2}{4k^2 - \theta^2}$, then $0 < r_1^* < r_0^*$, otherwise, $r_1^* = 0$; 3) it holds that $0 < r_2^* < r_0^*$. The proof of Proposition 3 is detailed in Appendix 5.

Proposition 3 shows that when the total government subsidy under two mechanisms is equal and low, the range of interest rate cut under green credit is larger than the subsidy rate of the government, as well as is larger than that under subsidy. However, people usually intuitively deem that the range of interest rate cut is identical to the subsidy rate of the government, which differs from the result of this study. The reason for this phenomenon is the leverage from the government subsidy mechanism.

In addition, when the total government subsidy exceeds a certain threshold, the bank will provide the manufacturer with interest-free credit service under the green credit mechanism; nevertheless, the interest rate of the bank under the subsidy mechanism is always positive. In other words, under the green credit mechanism, the government has a subsidy ceiling. When the total subsidy exceeds a certain threshold, the higher subsidy cannot bring more benefits, so the interest rate remains unchanged.

**Proposition 4.** 1) If $B_1 = B_2 < \frac{a^2k^2}{4k^2 - \theta^2}$, then $e_1^* > e_2^* > e_0^*$, $p_1^* > p_2^* > p_0^*$, $d_1^* > d_2^* > d_0^*$; 2) if $B_1 > 0$ and $B_2 \geq \frac{a^2k^2}{4k^2 - \theta^2}$, then $e_2^* \geq e_1^* > e_0^*$, $p_2^* \geq p_1^* > p_0^*$, $d_2^* \geq d_1^* > d_0^*$; 3) $r_0^* > r_2^* > r_1^*$. The proof of Proposition 4 is detailed in Appendix 6.

Proposition 4 shows that when the total government subsidy under two mechanisms is equal and low, under green credit, the product’s green degree and sales price are both the highest, the market demand is the largest, and the interest rate of the bank is the lowest. If the total government subsidy under subsidy mechanism is greater than a certain threshold, the product’s green degree, sales price and market demand under green credit mechanism are all higher than those under subsidy mechanism. From Proposition 3, it can be seen that the green credit mechanism has a subsidy ceiling, but the subsidy under the subsidy mechanism is unlimited. Therefore, when the total government subsidy under the subsidy mechanism is large enough, the subsidy mechanism is more conducive to green production than the green credit.

The profits of the bank and manufacturer under three scenarios (i.e., green credit, subsidy and non-subsidy) can be summarized in Table 1.

By comparing the profits of the bank and the manufacturer under different scenarios in Table 1, the following proposition can be obtained.

**Proposition 5.** 1) If $B_1 = B_2 < \frac{[p_2^*(\tilde{r}_2)]^2}{8(2k - \theta^2)}$, then $\Pi_1^{B*} > \Pi_2^{B*} > \Pi_0^{B*}$; if $B_1 > 0$ and $B_2 \geq \frac{[p_2^*(\tilde{r}_2)]^2}{8(2k - \theta^2)}$, then $\Pi_1^{B*} \geq \Pi_2^{B*} > \Pi_0^{B*}$, where $\tilde{r}_2 = \sqrt{\frac{(2k - \theta^2)^2 + 4k^2 - 2k}{2k - \theta^2}}$; 2) if $B_1 = B_2 < \frac{a^2\theta^2}{8(2k - \theta^2)}$, then $\Pi_1^{M*} > \Pi_2^{M*} > \Pi_0^{M*}$; if $B_1 > 0$ and $B_2 \geq \frac{a^2\theta^2}{8(2k - \theta^2)}$, then $\Pi_2^{M*} \geq \Pi_1^{M*} > \Pi_0^{M*}$.

The proof of Proposition 5 is detailed in Appendix 7.
Table 1. The profits of the bank and manufacturer under three scenarios

| Scenario      | Bank’s Profit, $\Pi^B_i$ | Manufacturer’s Profit, $\Pi^M_i$ |
|---------------|--------------------------|----------------------------------|
| Non-subsidy   | $\Pi^B_0 = \frac{a^2\theta^2}{16(2k-\theta^2)}$ | $\Pi^M_0 = \frac{a^2(4k-\theta^2)}{8(2k-\theta^2)}$ |
| Green credit  | $\Pi^B_1 = \frac{a^2\theta^2}{16(2k-\theta^2-2k\tau_1)}$ | $\Pi^M_1 = \frac{a^2(4k-\theta^2-4k\tau_1)}{8(2k-\theta^2-2k\tau_1)}$ |
| Subsidy       | $\Pi^B_2 = \frac{a^2\theta^2(1+\tau_2)^2}{16[2k-\theta^2(1+\tau_2)]}$ | $\Pi^M_2 = \frac{a^2[(4k-\theta^2(1+\tau_2))(1+\tau_2)]}{8[2k-\theta^2(1+\tau_2)]}$ |

Proposition 5 shows that when the total government subsidy under the mechanisms of green credit and subsidy are equal and low, the respective profits of the bank and the manufacturer under the green credit mechanism are higher than those under the subsidy mechanism. If the total government subsidy under the subsidy mechanism is greater than a certain threshold, then both the bank and the manufacturer prefer the subsidy mechanism to green credit. The reason for this phenomenon is similar to Proposition 4.

5.2. Social welfare and consumer surplus. In this study, social welfare can be regarded as follows:

Social welfare $= \text{Manufacturer’s profit} + \text{Bank’s profit} + \text{Consumer surplus} - \text{Government’s total subsidy}$ [6]. The function of the social welfare can be written as

$$SW_i = \Pi^B_i + \Pi^M_i + CS_i - B_i,$$

where the consumer surplus is

$$CS_i = \frac{(a - p_i + \theta e_i)^2}{2}.$$ 

We can achieve the following proposition by comparing the social welfare and the customer surplus in three scenarios.

**Proposition 6.** 1) If $B_1 = B_2 < \frac{[p^*_2(\hat{\tau}_2)]^2}{4\theta_2}$, then $SW^*_1 > SW^*_2 > SW^*_0$; if $B_1 > 0$ and $B_2 \geq \frac{[p^*_2(\hat{\tau}_2)]^2}{4\theta_2}$, then $SW^*_2 \geq SW^*_1 > SW^*_0$, where $\hat{\tau}_2$ satisfies the inequality $\frac{k(3k-\theta^2)}{16(2k-\theta^2-\theta^2\tau_2)} < \frac{(4k^2-\theta^2\tau_2)[2k^2-3k\theta^2+\theta^2\tau_2]}{2k-\theta^2(1+\tau_2)^2}$; 2) if $B_1 = B_2 < \frac{a^2k^2}{4k^2-\theta^2}$, then $CS^*_1 > CS^*_2 > CS^*_0$; if $B_1 > 0$ and $B_2 \geq \frac{a^2k^2}{4k^2-\theta^2}$, then $CS^*_2 \geq CS^*_1 > CS^*_0$.

The proof of Proposition 6 is detailed in Appendix 8.

Proposition 6 shows that when the total government subsidy under the mechanisms of green credit and subsidy are equal and low, the social welfare and customer surplus under the green credit mechanism are higher than those under the subsidy mechanism. If the total government subsidy under the subsidy mechanism is greater than a certain threshold, the social welfare and customer surplus under the subsidy mechanism are higher. Proposition 6 is similar in principle to Proposition 4. The results differ from those of Yang et al. [33], because they do not consider government budgets.

5.3. Environmental benefits. The government usually pays attention to social welfare in addition to environmental benefits. In this section, we will examine the effects of mechanisms of green credit and subsidy on the environmental benefits.
From Proposition 3, it can be seen that the green degree of a product produced by a manufacturer is higher under the green credit mechanism, indicating that the product is greener and more environmentally friendly. However, the greenness of a product only represents the degree of environmental protection of the product and cannot fully reflect the impact of the green products produced by the manufacturer on social and environmental benefits. Therefore, we regard the overall green degree of all sold products as an indicator that measures the environmental benefits, which equals to the number of products sold multiply by the green degree of a single product. The function of the environmental benefits can be written as

\[ SE_i = d_i e_i, \]  

(9)

We can achieve the following proposition by comparing the environmental benefits under three scenarios.

**Proposition 7.** 1) If \( B_1 = B_2 < \frac{a^2 k^2}{4 k^2 - \theta^2} \), then \( SE^*_1 > SE^*_2 > SE^*_0 \); if \( B_1 > 0 \) and \( B_2 \geq \frac{a^2 k^2}{4 k^2 - \theta^2} \), then \( SE^*_2 \geq SE^*_1 > SE^*_0 \).

The proof of Proposition 7 is detailed in Appendix 9.

Proposition 7 shows that when the total government subsidy under the mechanisms of green credit and subsidy are equal and low, the environmental benefits under the green credit mechanism are higher than those under the subsidy mechanism. If the total government subsidy under the subsidy mechanism is greater than a certain threshold, then the environmental benefits under the subsidy mechanism are higher. Proposition 7 is similar in principle to Proposition 4. The results also differ from those of Yang et al. [33].

To summarize, when the green product manufacturer has insufficient funds, the government provides subsidy for the bank or the manufacturer, which will not only increase the profit of the manufacturer, but also improve the environmental impact of manufacturer’s production. Moreover, it can be also indicated that the green credit mechanism is superior to the subsidy mechanism only when the total subsidy is low.

6. **Numerical simulations.** In this section, according to Equations (1)-(6), we employ several numerical examples to further examine the effects of the total government subsidy on the operational decisions and profits of the bank and the manufacturer under green credit and subsidy. To simplify the analysis, the parameters are set as \( a = 100, \theta = 1, \) and \( k = 1 \).

The effects of the total government subsidy on the optimal interest rate, the optimal green degree, the optimal sales price and demand under two mechanisms are shown in Figure 3. From Figure 3, we can conclude some results. When the total government subsidy exceeds a certain threshold, the optimal interest rate, optimal green degree, optimal sales price and demand under the green credit mechanism remain unchanged. In addition, when the total government subsidy is low, the green degree and demand of products under the green credit mechanism are higher than those under the subsidy mechanism. Otherwise, the opposite result will happen. These phenomena verify the conclusions in Propositions 3 and 4.

The effects of the total government subsidy on the profits of the bank and the manufacturer under two mechanisms are shown in Figure 4. And the effects of the total government subsidy on the social welfare and environmental benefits under two mechanisms are shown in Figure 5. We can also reach some results from Figures 4 and 5. Similarly, when the total government subsidy exceeds a certain threshold, the
enterprises’ profits, social welfare and environmental benefits under the green credit mechanism remain unchanged. In addition, when the total government subsidy is low, the green credit mechanism is superior to the subsidy mechanism; otherwise the subsidy mechanism would be better. These phenomena validate the conclusions in Propositions 5-7.

As shown in Figures 3-5, the reason for these results is that there is a subsidy ceiling under the green credit mechanism, while the subsidy under the subsidy mechanism is unlimited. Therefore, when the total government subsidy is large enough, the subsidy mechanism can continue to encourage the manufacturer to improve the green degree and expand the demand, but the green credit mechanism does not work.

Figure 3. The interest rate, product’s green degree, sales price and market demand

7. Extension. In this section, we investigate the government’s optimal subsidy rate by maximizing social welfare. According to Equation (7), we can know the optimal subsidy rates under the two mechanisms are \( \tau_1^* = \frac{2k - \theta^2}{4k} \) and \( \tau_2^* = \frac{8k - 3\theta^2}{4k + 3\theta^2} \), respectively.

Therefore, under the green credit mechanism, the optimal decisions of the bank and the manufacturer are \( r_1^* = 0, e_1^* = \frac{a\theta}{2k - \theta^2} \) and \( p_1^* = \frac{ak}{2k - \theta^2} \), respectively, and the demand is \( d_1^* = \frac{ak}{2k - \theta^2} \). The profits of the bank and the manufacturer are \( \Pi_{B1}^* = \frac{9a^2\theta^2}{16k^2 - 9\theta^2} \) and \( \Pi_{M1}^* = \frac{a^2\theta}{16k^2 - 9\theta^2} \), respectively.

Under the subsidy mechanism, the optimal decisions of the bank and the manufacturer are \( r_2^* = \frac{4k - 3\theta^2}{4k - 3\theta^2} \), \( e_2^* = \frac{3a\theta}{4k - 3\theta^2} \) and \( p_2^* = \frac{2ak}{4k - 3\theta^2} \), respectively, and the demand is \( d_2^* = \frac{2a\theta}{4k - 3\theta^2} \). The profits of the bank and the manufacturer are \( \Pi_{B2}^* = \frac{9a^2\theta^2k}{8k^2 - 6\theta^2} \) and \( \Pi_{M2}^* = \frac{12a^2\theta^2k}{16k^2 - 9\theta^2} \), respectively.
Thus, we can obtain the following proposition.

**Proposition 8.** $r^*_2 > r^*_1$; $e^*_2 > e^*_1$; $p^*_2 > p^*_1$; $d^*_2 > d^*_1$; $\Pi^B_2 > \Pi^B_1$; $\Pi^M_2 > \Pi^M_1$; $SW^*_2 > SW^*_1$; $SE^*_2 > SE^*_1$.

The proof of Proposition 8 is detailed in Appendix 10.

From Proposition 8, when the government decides the optimal subsidy rate, the subsidy mechanism can not only create higher profits for enterprises, but also bring greater social welfare and environmental benefits because the government subsidy is high enough.

8. **Conclusions.** This study proposes a leader-follower optimization model with the aim of maximizing the profits of the bank and the capital-constrained manufacturer. We obtain the optimal interest rate of the bank, the optimal green degree and sales price of the manufacturer under mechanisms of green credit and subsidy by solving the model. Through relevant theoretical analyses, the effects of the two mechanisms on the optimal operational decisions and profits of the bank and the manufacturer, as well as the social welfare and environmental benefits are compared. Some crucial conclusions are drawn in this study:

Firstly, no matter whether the government adopts mechanisms of green credit or subsidy, the green degree, sales price and market demand of the green product are all increasing in subsidy rate of the government. Furthermore, when the total government subsidy is low, the green degree, sales price and market demand of the
green product are all higher under green credit than those under subsidy. Otherwise, the result is opposite.

Secondly, the mechanisms of green credit and subsidy can both increase the profits of the bank and the manufacturer. When the total government subsidy is low, the profits of the bank and the manufacturer under the green credit mechanism are higher than those under the subsidy mechanism. In additions, when the total government subsidy exceeds a certain threshold, the bank and the manufacturer can gain more profits under the subsidy mechanism.

Thirdly, the mechanisms of green credit and subsidy can both increase the consumer surplus, social welfare and environmental benefits. Furthermore, when the total government subsidy is low, the consumer surplus, social welfare and environmental benefits under the green credit mechanism are higher; when the total government subsidy is large enough, they are higher under the subsidy mechanism.

Finally, when the government decides the optimal subsidy rate, the subsidy mechanism is superior to the green credit mechanism for the bank, the manufacturer and the government.

Based on the findings and results of this paper, the following management implications can be provided for the decisions of the government and the bank, as well as the financing and operational decisions of the capital-constrained green manufacturer.

Firstly, the capital-constrained manufacturer should adopt different product green design and pricing decisions depending upon different government incentive mechanisms.

Secondly, the bank plays a vital role in the capital-constrained green manufacturer’s production management. Financing service for the capital-constrained manufacturer by the bank can not only increase the bank’s profit, but also improve the overall social welfare and environmental benefits.

Finally, to stimulate the capital-constrained manufacturer to produce green products, providing direct or indirect subsidy to the manufacturers can improve the optimal profit of the manufacturer, in addition to the social welfare and environmental benefits. Especially under the circumstance of limited and relatively low budget, the government should adopt the green credit mechanism to support the manufacturer to develop green products, and the leverage effect of the government is the most obvious. If the government’s budget is sufficient, the subsidy mechanism is the best choice, which can bring higher economic and environmental benefits.

Although some useful results and managerial implications have been achieved in our work, there are some limitations. In reality, the market demand of green products is sometimes uncertain, which is not considered in this study. In addition, we do not emphasize other incentive mechanisms. Therefore, future work can be conducted in two aspects. Firstly, it is worth studying our research problem in the uncertain market. Secondly, the comparative study among various incentive mechanisms will be a future research focus.

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Appendix.

Appendix 1. Proof of Proposition 1. Firstly, we solve the optimal green degree and sales price of product. According to Equation (2), we can obtain $H(p_1, e_1) = \begin{bmatrix} -2 & \theta \\ \theta & -k(1+r_1) \end{bmatrix}$, it is easy to know that $\frac{\partial^2 \Pi_1}{\partial p_1^2} < 0$ and $\frac{\partial^2 \Pi_1}{\partial e_1^2} < 0$. The determinant of the Hessian can be found to be $\det H(p_1, e_1) = 2k(1+r_1) - \theta^2$. It is easy to know $\det H(p_1, e_1) > 0$. That is the $\Pi_1^* (p_1, e_1)$ is the joint concave function of $p_1$ and $e_1$, we can obtain the optimal green degree is $e_1^* = \frac{ak(1+r_1)}{2k(1+r_1) - \theta^2}$, and the sales price is $p_1^* = \frac{ak(1+r_1)}{2k(1+r_1) - \theta^2}$.

Putting $e_1^*$ into Equation (1), after some algebra work, we have $\frac{\partial \Pi_1}{\partial r_1} = \frac{k a^2 \theta^2 (2k - \theta^2 - 4k r_1 - 2k r_1)}{2[2k(1+r_1) - \theta^2]^2}$, let $\frac{\partial \Pi_1}{\partial r_1} = 0$, we can obtain $r_1^* = \frac{2k - \theta^2 - 4k r_1}{2k}$. Then let $g(r_1) = \frac{\partial \Pi_1}{\partial r_1}$, it is easy to know that when $r_1 \leq r_1^*$, $g(r_1)$ is a decreasing function of $r_1$, and when $r_1 > r_1^*$, $g(r_1)$ is also a decreasing function of $r_1$, therefore it holds that $\frac{\partial^2 \Pi_1}{\partial r_1^2} < 0$, namely $r_1^*$ is the unique optimal solution. When $r_1 = 0$, we have the interest rate $r_1^* = \frac{2k - \theta^2}{2k}$. Hence, Proposition 1 holds.

Appendix 2. Proof of Corollary 1. According to Proposition 1, we are easy to know $\frac{\partial \Pi_1}{\partial e_1} = -\frac{\theta}{k} < 0$. Similarly, we can show others. Hence, Corollary 1 holds.

Appendix 3. Proof of Corollary 2. According to Proposition 1, we are easy to know $\frac{\partial \Pi_2}{\partial p^2} = -\frac{\theta}{k} < 0$. Similarly, we can show others. Hence, Corollary 2 holds.

Appendix 4. Proof of Proposition 2. Firstly, we solve the optimal green degree and sales price of product of. According to Equation (5), we can obtain $H(p_2, e_2) = \begin{bmatrix} -2(1+\tau_2) & \theta (1+\tau_2) \\ \theta (1+\tau_2) & -k(1+\tau_2) \end{bmatrix}$, it is easy to know that $\frac{\partial^2 \Pi_2}{\partial p_2^2} < 0$ and $\frac{\partial^2 \Pi_2}{\partial e_2^2} < 0$. The determinant of the Hessian can be found to be $\det H(p_2, e_2) = (1+\tau_2)^2 \frac{2k(1+r_2) - \theta^2}{2k(1+r_2) - \theta^2}$. It is easy to know that $\det H(p_2, e_2) > 0$. That is the $\Pi_2^* (p_2, e_2)$ is the joint concave function of $p_2$ and $e_2$, we can obtain the optimal green degree is $e_2^* = \frac{\alpha(1+\tau_2)}{2k(1+r_2) - \theta^2(1+r_2)}$, and the sales price is $p_2^* = \frac{ak(1+r_2)}{2k(1+r_2) - \theta^2(1+r_2)}$.

Putting $e_2^*$ into Equation (4), after some algebra work, we have $\frac{\partial \Pi_2}{\partial r_2} = \frac{k a^2 \theta^2 (1+\tau_1)(2k(1-r_2)-\theta^2(1+r_2))}{2[2k(1+r_1) - \theta^2]^2}$, let $\frac{\partial \Pi_2}{\partial r_2} = 0$, we can obtain $r_2^* = \frac{2k - \theta^2 (1+r_2)}{2k}$. Then let $f(r_2) = \frac{\partial \Pi_2}{\partial r_2}$, it is easy to know that when $r_2 \leq r_2^*$, $f(r_2)$ is a decreasing function of $r_2$, and when $r_2 > r_2^*$, $f(r_2)$ is also a decreasing function of $r_2$, therefore it holds that $\frac{\partial^2 \Pi_2}{\partial r_1^2} < 0$, namely $r_2^*$ is the only unique optimal solution. Hence, Proposition 2 holds.

Appendix 5. Proof of Proposition 3. 1) When $\frac{\theta}{k} = \tau_2 \neq 0$, we have $e_1^* = e_2^*$, $p_1^* = p_2^*$ and $d_1 = d_2$. Because $B_1 = \frac{1}{2} k e_1^2 r_1$, $B_2 = p_2 d_2 r_2$, $pd > \frac{1}{2} k e_2^2$, $\tau_1 > \tau_2$, we have $B_1 < B_2$. When $B_1 = B_2 > 0$, that is $\frac{\theta}{k} > \frac{1}{2}$, we have $r_2^* - r_1^* = 2r_1 - \frac{\theta^2}{2k} r_2 > 2r_1 - \frac{\theta^2}{2k} r_2$. Because of $\frac{\theta^2}{2k} < 1$, we have $r_2^* > r_1^*$, that is $\Delta r_1 = \Delta r_2 = r_2^* - r_1^* > 0$; 2) when $0 < B_i < \frac{\theta^2}{8(2k - \theta^2)}$, we have $\tau_1 < \frac{2k - \theta^2}{4k}$, so $0 < r_1^* < r_0^*$, otherwise $r_1^* = 0$;
3) when $B_i > 0$, to ensure its profit to be positive under the subsidy mechanism, the optimal interest rate of the bank must be met $r_i^* > 0$, so we have $0 < r_i^* < r_0^*$. Hence, the Proposition 3 holds.

**Appendix 6.** Proof of Proposition 3. According to Proposition 1, $e_1^*, p_1^*, d_1^*$ are monotonically increasing functions of $τ_1$, then $B_1$ is also a monotonically increasing function of $τ_1$. Similarly, according to Proposition 2, $e_2^*, p_2^*, d_2^*$ are monotonically increasing functions of $τ_2$, then $B_2$ is also a monotonically increasing function of $τ_2$.

1) When $\frac{r_2}{1 + r_2} = τ_2 \neq 0$, we have $e_1^* = e_2^*$, $p_1^* = p_2^*$ and $d_1^* = d_2^*$. Because $B_1 = \frac{1}{2} e_1^2 τ_1$, $B_2 = p_2 d_2 τ_2$, $pd > \frac{1}{2} ke^2$, $τ_2 > τ_1$, we have $B_1 < B_2$. In additions, when $B_1 = B_2 = 0$, we have $e_1^* = e_2^* = ε$, $p_1^* = p_2^* = p_0$ and $d_1^* = d_2^* = d_0^*$. Therefore, we can know when $B_1 = B_2 < \frac{a^2 k^2}{4 k^2 - θ^2}$, $e_1^* > e_2^* > e_0^*$, $p_1^* > p_2^* > p_0^*$ and $d_1^* > d_2^* > d_0^*$ hold.

2) When $B_2 ≥ \frac{a^2 k^2}{4 k^2 - θ^2}$, that is $τ_2 ≥ \frac{2 k - θ^2}{2 k - θ^2}$, it is easy to know that $e_2^* ≥ \frac{aθ^2}{k^2 - θ^2}$ is the maximum $\{e_1^* (τ_1)\}$, thus $e_2^* > e_1^* > e_0^*$. Similarly, we have $p_2^* > p_1^* > p_0^*$ and $d_2^* > d_1^* > d_0^*$.

3) When $B_1 = B_2 > 0$, that is $\frac{r_2}{1 + r_2} < τ_1$, we have $r_2^* - r_1^* = 2τ_1 - \frac{θ^2}{2k} r_2 > \frac{θ^2}{2k} r_2 - \frac{θ^2}{2k}$. Because $\frac{θ^2}{2k} < 1$, so $r_2^* > r_1^*$. And we also know $r_0^* - r_1^* = 2τ_1 - \frac{θ^2}{2k} r_2 > 0$, thus it holds that $r_0^* > r_2^* > r_1^*$. Hence, the Proposition 4 holds.

**Appendix 7.** Proof of Proposition 5. When $B_1 = B_2$, $Π_1^B$ is a monotonically increasing function of $τ_1$, so $Π_1^B > Π_0^B$. From $Π_1^B > Π_2^B$, we can obtain $τ_2 > \sqrt{(2k - θ^2)^2 + 4k^2 - 2k}$, thus when $B_2 ≥ [p_2^* (\bar{τ}_2)]^2 \bar{τ}_2$, $Π_2^B ≥ Π_1^B > Π_0^B$ holds, where $\bar{τ}_2 = \sqrt{(4k - θ^2)^2 + 4k^2 - 2k}$. Similarly, we can show others. Hence, the Proposition 5 holds.

**Appendix 8.** Proof of Proposition 6. The proof of Proposition 6 is similar to the proof of Proposition 5. Hence, the Proposition 6 holds.

**Appendix 9.** Proof of Proposition 7. According to Proposition 4, we can know that the Proposition 7 holds.

**Appendix 10.** Proof of Proposition 8. It is easy to know that $r_2^* = \frac{4k - 3θ^2}{4k - 3θ^2} > 0 = r_1^*$. When the government decides the optimal subsidy rate, the total subsidy of the government under the two mechanisms are $B_1^* = \frac{a^2 θ^2 k}{2(2k - θ^2)}$ and $B_2^* = \frac{4a^2 k^2 (8k - 3θ^2)}{(4k - 3θ^2)(4k + 3θ^2)}$. Because $B_2^* = \frac{4a^2 k^2 (8k - 3θ^2)}{(4k - 3θ^2)(4k + 3θ^2)} > \frac{4k^2}{4k^2 - θ^2}$, according to Proposition 4, we have $e_2^* > e_1^*$. Similarly, we can show others. Hence, the Proposition 8 holds.

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