Green Credit Financing versus Trade Credit Financing in a Supply Chain with Carbon Emission Limits

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Abstract: Green credit financing (GCF) is a type of financial service provided by banks to encourage borrowers to commit green investment and achieve sustainable development. This study investigates a supply chain system consisting of a capital-constrained manufacturer and a well-funded supplier facing uncertain demand, in which the manufacturer may seek GCF from banks. An important prerequisite for obtaining a green loan is that the borrower must make green upgrades and ensure compliance with pre-specified environmental standards. We design a GCF model for a supply chain by imposing a hard constraint on carbon emissions. To determine the effectiveness of GCF, we conduct an in-depth analysis comparing the GCF with traditional trade credit financing (TCF), in which excessive carbon emissions are penalized. The optimal equilibrium solutions under GCF and TCF mode are obtained and their sensitivities to key parameters analyzed. Concerning the preferences of the two financing strategies, we find that under a relatively strict carbon emission policy, the manufacturer can set an appropriate green investment range to achieve a win-win situation with the supplier. Finally, we compare the social welfare of the supply chain for the different financing modes and find that there are regions in which both the social welfare and profit of the manufacturer can be a win-win. The government can guide manufacturers to make a win-win choice by setting different carbon caps.

Keywords: Supply chain management; Carbon emission; Green credit; Trade credit; Game theory

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1. Introduction

In the past decade, increasingly serious environmental problems have attracted much attention from governments and the public sector (Chu et al., 2017; Joo & Suh, 2017). To reduce firms' carbon emissions, many governments have promulgated various policies for sustainability awareness and decreased environmental impacts of firms' operational activities. Early in 1997, the Kyoto Protocol established an emission trade mechanism and carbon emissions cap for each country, which effectively limits carbon emissions. The UK has launched a Carbon Reduction Commitment (CRC), which is a mandatory scheme aimed at cutting carbon emissions by 1.2 million tons per year by 2020 (https://www.carbonfootprint.com). China, as one of the major carbon emitters, has also implemented a series of measures and, to achieve its emission reduction targets, the Ministry of Environmental Protection has warned that companies that cannot upgrade and reduce emissions will have to close within a certain timeframe (http://china.cnr.cn/gdgg/20170714/t20170714_523850712.shtml). Under such great environmental pressure, enterprises in China have had to upgrade their production by investing in green technologies, which is undoubtedly aggravating their capital constraints (Cao & Yu, 2018). In developing countries, firms with low credit ratings and high default risk struggle to access finance from traditional banks (Chen, 2015; Jing, Chen, & Cai, 2012; Zhou, Wen, & Wu, 2015). Thus, lack of financial resources may discourage and demotivate such capital-constrained firms from tackling sustainability or environmental issues (Walker & Preuss, 2008).

To support enterprises' green investment and alleviate their financial distress, banks throughout the world have launched green credit financing (GCF). GCF is a kind of green financial service for investment in sustainable development projects and initiatives, aimed at encouraging firms' green investment (Höhne, Khosla, Fekete, & Gilbert, 2012). The unique characteristic of GCF is that such financing is subject to a hard constraint or condition concerning carbon emissions. The purpose of GCF is to motivate enterprises to make green upgrades for sustainable operations, and an important prerequisite for obtaining a loan is compliance with environmental monitoring standards (http://www.cbrc.gov.cn). It should be pointed out that GCF is very different from bank financing under a cap-and-trade mechanism because the latter does not require any condition for obtaining financing; it imposes only a linear cost/profit function with respect to carbon emissions against a pre-specified cap. GCF is often implemented by imposing certain hard constraints on environmental performance indicators. An important approach in green finance is the decarbonizing of investor portfolios, in which the companies are financed subject to limiting their ecological footprint. BNP Paribas aligned its financing and investment activities with the Paris agreement on carbon emission. If companies fail to meet their emissions standards, the bank will stop lending to them. BNP Paribas financed Danone (the French food products company) on the condition that Danone could provide documented targets of their future carbon intensity and the strategy for aligning their activities with the Paris Agreement targets. Besides, BNP Paribas Asset Management has tightened its green financing policy on companies engaged in generating electricity; it excludes the power generators whose carbon intensity exceeds 491 gCO_2/kWh (the 2017 global average) and will lower the threshold to 327 gCO_2/kWh by 2025 to fall in line with the International Energy Agency's (IEA) Sustainable Development Scenario(https://www.bnpparibas-am.com/).

Another example is China's Shenzhen Xiangkong Technology Co., Ltd., who obtained a loan of 7.5 million Chinese yuan from the Industrial Bank after submitting a greenhouse gas emission reduction certification report (http://2011.cma.gov.cn/qhbh/newsbobao/201001/t20100107_56224.html). Besides, Huarong Xiangjiang Bank of China adopts a strict policy on green loan applications subject to the condition that the company must meet the environmental protection standards. A common phenomenon in the above examples is that if a company wants to obtain a green loan from the bank, it must meet the green credit's strict requirements on the company's emissions. Hence, this paper proposes hard constraints on carbon emission under GCF.

The downside of using GCF to upgrade companies' green technologies is that they have to shoulder the financial risk by themselves. Inspired by these cases and other practices, this study analyzes the influence of GCF on firms' financial equilibrium and social welfare.

Traditionally, in the context of supply chains, another way to solve firms' capital constraints is trade credit financing (TCF) (Chen, 2015). Generally, TCF is a deferred payment financing mode between an upstream supplier and downstream manufacturer in capital-constrained supply chains; the upstream supplier may act as an investor in addition to the conventional role of providing products (Chen, 2015). In other words, TCF permits the delay of payments (Wang, Zhao, & Peng, 2018; Zhou, Cao, Zhong, & Wu, 2017). TCF is widely used in the U.S., by approximately 60% of firms, rendering it the second most popular financing option after bank finance (https://www.investopedia.com/terms/t/trade-credit.asp). Under increasingly strict environmental policies, if a firm's carbon emissions exceed a threshold, it faces punishment by an environmental protection administration. For instance, Chalco Shandong Co., Ltd, which produces alumina, was fined 200,000 yuan for pollution in 2018 (http://www.tanjiaoyi.com/article-26998-1.html). Cao, Du, & Ruan (2019) demonstrated that a capital-constrained manufacturer seeks finance from its upstream supplier if it decides to undertake a green investment, and Huang, Ying, Yang, & Hassan (2019) pointed out that trade credit has a significant and positive impact on sustainable economic development.

As mentioned above, on one hand, if an enterprise chooses GCF, then it has to bear the financial risk by itself after upgrading technology but enjoys a far lower interest rate than under TCF, which greatly reduces the pressure from loan repayments. On the other hand, if the firm chooses TCF, then the credit is an internal deferred capital transfer in a cooperation agreement between the upstream supplier and downstream manufacturer. The supplier not only acts as an operator, but also a financier, which bears the financial cost and repayment risks of the downstream manufacturer. Therefore, it is necessary to figure out which financing mode is more suitable for green investment and under what circumstance.

Researchers have paid significant attention to carbon emissions in operations management (Guo, Liu, Liu, & Guo, 2017; Li, Xu, Deng, & Liang, 2017; Reefke & Sundaram, 2017). However, to the best of our knowledge, few studies have examined carbon emission under GCF or compared GCF and TCF. To fill this research gap, our study considers a supply chain consisting of a supplier and a manufacturer in a newsvendor setting, facing a tightening government carbon emissions policy. The manufacturer intends to invest in green technology to reduce carbon emissions and meet green production requirements. Since it is costly for the manufacturer to invest in low-emission facilities, we analyze and compare two financing modes—GCF from a bank and TCF from a supplier—and examine the social welfare of the supply chain concerning different financing modes. We aim to answer the following questions. (1) When a hard constraint is imposed on emissions under GCF, and a soft constraint on emissions under TCF, which of these two financing methods is more effective and requires the higher environmental performance of enterprises? (2) What are the influences of green investment on the supply chain's operational decisions? (3) Which financing mode, GCF or TCF, is better for upstream and downstream enterprises as well as overall social welfare?

This study makes the following contributions. First, we consider the decisions for a capital-constrained manufacturer facing the challenge of reducing carbon emissions in a supply-chain context, whereas the related literature predominantly has assumed that firms are well funded (e.g., Du, Hu, & Song, 2014; Xu, He, Xu, & Zhang, 2017a; Xu, Zhang, He, & Xu, 2017b). Second, to the best of our knowledge, there is little research focusing on operational decisions under GCF. We are the first to incorporate GCF into supply chain management. We analyze and evaluate the impact of GCF on channel members' operational decisions. Third, we conduct a comparative analysis of the GCF and TCF modes to identify their relative preference from supply chain members' perspectives and compare social welfare with regard to different financing modes.

The rest of the paper is organized as follows. The next section reviews the relevant literature. Section 3 defines the relevant notations, presents the mathematical model, and derives the equilibrium solutions under GCF and TCF strategies, including the optimal production quantity and wholesale price. Section 4 compares the financing equilibriums between GCF and TCF. We conduct a series of numerical analyses in Section 5 to compare the performance of the supply chain under the two financing strategies. Section 6 compares social welfare under different financing modes. We explore the scenario that the green investment is also a decision variable of the manufacturer in Section 7. Section 8 draws conclusions.

2. Literature review

This study is related to the literature in two research streams: (i) carbon emission reduction within operational decisions; and (ii) operational decisions under supply chain financing (SCF).

In the first research stream, based on the review of Waltho, Elhedhli, & Gzara (2019), the common policies used to reduce carbon emission are carbon caps, carbon taxes, a cap-and-trade mechanism, and carbon offsets. This study mainly focuses on carbon caps. Thus, we first review the literature on carbon caps and cap-and-trade in operations management. A carbon cap is an emission allowance allotted by a regulatory authority and is an effective way to restrict carbon emissions. Some studies have introduced a carbon emission constraint to their models to limit emissions within the cap or subject to production capacity. For instance, using a stochastic model, Drake, Kleindorfer, & Wassenhove(2016) investigated the impact of a cap-and-trade regime on firms' capacity decisions and found that firms' expected profits were greater and carbon emissions lower under the cap-and-trade mechanism than the ones under emissions tax mode. Benjaafar, Li, & Daskin (2013) and Zhang & Xu (2013) considered cap-and-trade policies and carbon taxes. Benjaafar, Li, & Daskin (2013) analyzed inventory management decisions using only operational adjustments for carbon reduction. Zhang & Xu (2013) used a linear computational solution to present the impact of a carbon cap on capacity and production decisions.

Other studies have treated carbon caps as a punishment mechanism within the profit function, that is, a firm's expected profit would be reduced if the firm's emissions exceeded the cap. For instance, Xu, Chen, & Bai (2016) analyzed operational decisions under a cap-and-trade mechanism in a two-tier supply chain. Under a make-to-order setting, they considered two contracts to coordinate the system and found that a two-part tariff contract generated fewer carbon emissions and higher profits. Song, Govindan, Xu, Du, & Qiao (2017) studied operation and capacity expansion problems under a cap-and-trade mechanism and found that the firm prefers to expand capacity only when its capacity investment is relatively low and marginal profit is sufficiently high. Also using a cap-and-trade mechanism, Xu, Zhang, He, & Xu (2017b) investigated production and pricing problems within a make-to-order setting, in which the manufacturer produces two products and sells them to a single monopolistic retailer. Contrary to expectations, the authors found that production quantity decreased under the carbon cap in certain conditions. Bai, Yale, Jin, & Xu (2019) studied a low carbon supply chain consisting of a manufacturer and two competing retailers, in which the manufacturer invested in green technologies under a cap-and-trade regulation. The authors found that carbon emissions in the centralized system were lower than that in the decentralized system. As seen, the abovementioned literature has paid more attention to operational decisions under a carbon cap but has not considered possible capital constraints in supply chains.

The second research stream closely related to ours comprises operational decisions under SCF. SCF refers to the integration of financial concerns with supply chain members' operational decisions (Ding, Dong, & Kouvelis, 2007), and is particularly important when firms face the problem of capital constraints(Yan, Liu, Xu, & He, 2020). For example, Cai, Chen, &Xiao (2014), Chen & Cai (2011), and Jing, Chen, & Cai (2012) integrated financial concerns with operational decisions under stochastic demand, and newsvendor models were presented to solve the capital-constraints problem. Dada & Hu (2008) discussed a budget-constrained newsvendor with bank credit financing and found that the firm would procure less than that under an ideal situation when given a lower borrowing cost. Chao, Chen, & Wang (2012) established a multi-period inventory model and found that the incorporation of financial considerations and operational decisions was essential for retailers to cope with capital constraints. Kouvelis & Zhao (2016) discussed the relationship between a retailer's optimal order quantity and different bankruptcy costs. Gao, Fan, Fang, & Lim (2018) studied SCF problems using a peer-to-peer lending platform and identified supply chain members' operational decisions when either the retailer or the manufacturer is capital constrained. All of the abovementioned studies have adopted the newsvendor setting, in which demand is stochastic because the fluctuation of demand could trigger bankruptcy risk.

Under such a setting, much research has compared different financing methods (Cai, Chen, & Xiao, 2014; Jing, Chen, & Cai, 2012). The most common financing methods are bank credit finance (BCF), which is funded by banks, and TCF, which is supported by upstream suppliers. Cai, Chen, & Xiao (2014) developed a newsvendor and principal-agent model to investigate a capital-constrained retailer under TCF and BCF, and explored two scenarios: one credit mode and two credit modes. The authors showed that the retailer's preference for credit types depends on market competition and the risk level of transition by characterizing the optimal interest, credit size, and order quantity. Jing, Chen, & Cai (2012) analyzed a supply chain system consisting of a supplier and a capital-constrained retailer under both BCF and TCF modes. The authors concluded that BCF was preferred by the retailer when only one credit mode is viable, because of lower wholesale prices, but when both modes are viable, TCF is the better choice when given a relatively low production cost. Zhou, Cao, & Zhong (2017) studied the optimal ordering and advertising policy of a budget-constrained retailer and compared BCF with the supplier/mixed financing decisions. Also comparing TCF and BCF, Lu & Wu (2020) considered the impact of tax on financing decisions of the multinational retailer who was facing financial constraints. In addition, there is some literature comparing the traditional TCF(BCF) financing with some new or hybrid financing modes, such as Li, An, & Song (2018) studied operational decisions under two financing methods: TCF and partial credit guarantee (PCG). The authors found that there is a region in which the optimal performances of both players under TCF are higher than those under PCG. Jin & Wang (2020) designed financing strategies composing of trade credit and full (partial) factoring, and compared them with the single trade credit to investigate the suppliers' best performance. Wang, Fan, & Yin (2019) compared electronic business financing (EBF) and BCF and found that active EBF can coordinate the supply chain. Jin, Zhang, & Luo (2019) considered and compared the non-collaborative strategy (bank financing) and two collaborative strategies (bank financing with trade credit, BCF with the supplier's guarantee), they found that if the leader performed as a guarantor instead of an intermediary creditor, the supply chain members would have better performance. The abovementioned studies have focused on the financing strategies in supply chains under capital constraints, but have ignored the influence of carbon emissions.

In recent years, some literature has begun to pay attention to the impact of green credit on enterprise decision-making and government policy-making. For example, some literature investigates the impact of green credit and government subsidies on corporate and social welfare (e.g. Huang, Fan, & Wang, 2020; Yang, Chen, Yang, & Nie, 2019; Huang, Fan, & Wang, 2017). Green credit is equivalent to the bank providing subsidies to enterprises. This group of literature focuses on comparing the suitable conditions for different incentive mechanisms and provides references for the government to formulate and implement subsidy policies. There are also some studies about the impact of green credit on manufacturers' efforts to reduce pollution, such as Kang, Jung, & Lee (2020). The above literature considers the impact of green credit on enterprises under deterministic demand. Different from them, this paper considers the impact of random demand fluctuation on enterprise financing decision-making and focuses on the selection of different financing modes from the perspective of enterprises. Some articles examine green credit under random demand, such as Fang & Xu (2020). Unlike them, our paper considers the entry threshold of green credit, that is, the hard constraint to obtain green credit.

The most closely related studies to ours are Cao, Du, & Ruan(2019) and Dash, Yang, & Olson (2018). Dash, Yang, & Olson (2018) characterized the carbon reduction level under BCF and TCF modes and found that the supply chain performed better when the manufacturer invests in reducing emissions. Different from their setting, we examine a carbon emission constraint problem under GCF and carbon emission punishment under TCF. Under GCF, the bank requires the carbon emission constraint to issue green credit, that is, the hard constraint on carbon emission is the condition for the bank to issue GCF. Under TCF, the government implements carbon emission punishment as an environmental protection restriction, which is a soft constraint applied in SCF (due to this mode being more profit-driven). In fact, under GCF, firms also face punishment for carbon emissions. However, within the threshold of a green loan constraint, the companies cannot breach the threshold. Besides, we compare the two financing strategies and evaluate social welfare under the two modes. Cao, Du, & Ruan(2019) compared TCF and BCF under a cap-and-trade mechanism. In their research, the cap-and-trade mechanism may be regarded as a soft constraint to encourage firms to reduce carbon emissions voluntarily, because the bank loan is always available. Different from their setting, we apply a hard constraint on carbon emissions, which is the condition for the bank to issue green credit. If the carbon emissions exceed the standard, the manufacturer does not obtain green credit. Adding a constraint to the manufacturer's optimization problem not only makes the problems more demanding and interesting, but also complements the study of Cao, Du, & Ruan(2019). Their results showed that TCF is the manufacturer's financing equilibrium, which is irrelevant to carbon abatement investments. However, our results demonstrate that the supplier's financing equilibrium is closely related to the green investment, which is somewhat contrary to the finding of Cao, Du, & Ruan(2019). To the best of our knowledge, we are the first to analyze the impact of GCF in supply chain management. Our methods and findings complement the results of Cao, Du, & Ruan(2019) and Dash, Yang, & Olson (2018).

3. The model and analysis

3.1 Model description

We model the supply chain as a Stackelberg game between the supplier (referred to as "she") and the manufacturer (referred to as "he"), in which the supplier acts as a leader and the manufacturer as a follower. We limit the decisions to a single period and take a full-information setting. We consider two cases: first, the manufacturer undertakes green production to reduce carbon emissions and obtains a green loan from a bank, which is referred to as GCF; second, the manufacturer applies a delayed payment (trade credit) service from the supplier, which is referred to TCF. We assume that the manufacturer can obtain finance only via GCF or via TCF, that is, the lending is exclusive.

At the beginning of the period, the supplier publishes her wholesale price per product for both financing modes. (1) The wholesale price w^G under GCF is available at time zero. (2) The wholesale price w and interest rate under TCF are available at time zero, and the price is a postponed wholesale price w^T at the end of the period (Jing, Chen, & Cai, 2012; Kouvelis & Zhao, 2017). After observing w^G and w^T, the manufacturer sets the production quantity to maximize his profit and undertakes green investment K_t. The unit production cost of the supplier is c, and the price p is exogenously given.

According to research by the China Climate Communication Project Center during the COP23 Bonn Climate Conference, that 73.7% of the Chinese public is willing to spend more on climate-friendly products and 27.5% of Chinese people are willing to pay the full price for their carbon emissions (http://www.weather.com.cn/zt/tqzt/2790512.shtml). Improved environmental performance from the green investment may increase consumer utility, which results in higher demand (Bi, Jin, Ling, & Yang, 2016; Cao, Du, & Ruan, 2019; Dong, Shen, Chow, Yang, & Ng, 2016).

Thus, we assume that demand D is random and depends on green investment such that $D = A + \delta\sqrt{K_t} + \varepsilon$, the random demand variable has an *increasing generalized failure rate* (*IGFR*). Suppose ε is a nonnegative random variable with distribution function $F(\varepsilon)$ and density function $f(\varepsilon)$ on $(0,+\infty)$. Let $\bar{F}(\varepsilon) = 1 - F(\varepsilon)$ be the reliability function of ε. The increasing generalized failure rate of ε defined by Lariviere & Porteus (2001) is $g(\varepsilon) = \varepsilon h(\varepsilon)$, where $h(\varepsilon) = f(\varepsilon)/\bar{F}(\varepsilon)$ is the failure rate of ε. The properties of *IGFR* contain: (1)The failure rate $h(\varepsilon)$ is increasing in ε; (2)The $g(\varepsilon)$ is monotonically increasing in ε. (3) $d\varepsilon f(\varepsilon)/d\varepsilon > 0$ (Lariviere, 2006, Corollary 1). This is a common assumption for random customer demand in supply chain modeling and it captures most common distributions(Banciu & Mirchandani, 2013), the similar can be seen in Jing, Chen, & Cai (2012); Chen, (2015); Deng, Gu, Cai, & Li (2018); Chen, Cai, & Song (2019); Peng & Zhou (2019). The parameter A represents the basic market size, δ denotes the increase in demand per unit of green investment (Dong, Shen, Chow, Yang, & Ng, 2016), K_t represents the green investment level, such as upgrading the technology level or purchasing an emission reduction facility (Pei, Toombs, & Yan, 2014). Demand is realized after the selling season, we assume that the manufacturer is a long-running and creditworthy company that is undergoing a green technology upgrade, which means that the firm will do his best to repay all loan obligations. In case the manufacturer's income is not enough to cover his repayment, we assume that he will continue operating the business with negative cash flow by fully repaying the loan. The similar settings have been adopted in the literature (e.g., Hu & Sobel, 2007; Li, Shubik, Sobel, & Shubik, 2013; Stauffer, 2006; Zhou, Cao, & Zhong, 2017). Although demand uncertainty may result in leftover stock and inventory, to simplify exposition, we ignore the goodwill loss due to inventory and omit the salvage value (Cao & Yu, 2018; Jin, Zhang, & Luo, 2019; Tunca & Zhu, 2017; Zhou, Wen, & Wu, 2015). The supply chain members aim to maximize their expected period-end capital.

The notations are defined as follows:

c: the unit production cost of the supplier

p: the unit price of the product, which is exogenously given

c_e: the penalty (punishment) of unit excessive carbon emissions

D: the stochastic demand of the manufacturer

A: the basic market size

δ: demand increasing per unit of green investment

ε: a random variable

K: the manufacturer's initial capital

K_t: the green investment of the manufacturer, which represents the money invested in the green improvement

R: the interest rate of the commercial bank

R_s: the supplier's deferred interest rate

T: the carbon emission cap required by the bank or the government

t: the manufacturer's initial cap emissions per unit production.

θ: the unit carbon emission reduction due to green investment

q: the production quantity of the manufacturer, which is the decision variable

w^G: the unit wholesale price of the supplier under GCF, which is the decision variable

w: the wholesale price under TCF at time zero

w^T: the postponed wholesale price of the supplier $w^T = w(1+R_s)$ at the end of the period under TCF, which is the decision variable

w^{GB} (w^{TB}): the wholesale price with no carbon emission constraint under GCF (TCF)

w^{GL} (w^{TL}): the wholesale price with the carbon emission constraint of GCF (TCF).

In the following, the superscripts *G* and *T* represent the two cases under GCF and TCF, respectively, and the subscripts *m* and *s* represent the manufacturer and supplier, respectively.

3.2 Green credit financing mode

Under GCF, the manufacturer seeks green credit finance from the bank because of capital constraints. At the beginning of the period, the supplier publishes her wholesale price, and after observing it, the manufacturer decides his production quantity and undertakes his green investment, we assume that the initial capital of the manufacturer can cover his green investment ($K \geq K_t$); the bank offers the manufacturer GCF only if his carbon emissions do not exceed a certain carbon cap *T*, which is imposed by the government.

Specifically, we assume that the supplier first publishes her wholesale price w^G, the manufacturer then decides his production quantity q^G and undertakes his green investment. Furthermore, with the manufacturer's commitment to constrained carbon emissions, the bank issues green loans $w^G q^G + K_t - K$ to the manufacturer and assesses the carbon emission level in the whole process. If the manufacturer defaults, that is, his carbon emissions exceed the standard, the bank immediately announces the suspension of the loans and requests loan recovery, which results in the bankruptcy of the manufacturer. Therefore, to avoid this trivial situation, we assume that the carbon emissions of the manufacturer are limited by a specified carbon cap. At the end of the period, the manufacturer generates revenue $E[p\min\{D,q^G\}]$ and repays his loans plus interest to the bank, which is $(w^G q^G + K_t - K)(1+R)$.

In this case, we can define the manufacturer's end-period cash flows, which include the expected revenues from selling in the market, and the repayment with interest to the bank, denoted by π_m^G. Therefore, the manufacturer's optimization problem can be formulated as

$$E[\pi_m^G(q^G)] = E[p\min\{D,q^G\}] - (w^G q^G + K_t - K)(1+R),$$

$$s.t.\quad (t - \theta K_t)q^G \le T \quad .$$

Here, the manufacturer maximizes his end-period cash flow by deciding his production quantity. t means the initial carbon emissions per unit of production quantity, θK_t means the emission reduction per unit due to the green investment and $(t - \theta K_t)q^G \le T$ means that carbon emissions are constrained by *T*, which is given by the government (Dong, Shen, Chow, Yang, & Ng, 2016). Lemma 1 describes the reaction function of the production quantity.

Lemma 1. Under GCF mode, given the wholesale price w^G of the supplier, the capital-constrained manufacturer's unique best response of the optimal production quantity q^{G*} is given as

$$q^{G*} = \begin{cases} F^{-1}\left(\dfrac{p - w^G(1+R)}{p}\right) + A + \delta\sqrt{K_t}, & T \ge T^G \\ \dfrac{T}{t - \theta K_t}, & T < T^G \end{cases},$$

where $T^G = (t - \theta K_t)[F^{-1}(\dfrac{p - w^G(1+R)}{p}) + A + \delta\sqrt{K_t}]$.

The proof is in the Appendix.

Lemma 1 indicates that the optimal production quantity is determined by two sets of strategies corresponding to the value of the carbon emission cap T. When $T \ge T^G$, the carbon emission cap is relatively relaxed, we call it under the high carbon emission(HCE) condition; and when $T < T^G$, the carbon emission cap is relatively tight, we call it under the low carbon emission(LCE) condition. On the one hand, there is a threshold value of the carbon emission T^G, above which the manufacturer's optimal production quantity depends only on the operational parameters, and he can set his production quantity as the optimal one to maximize his utility. This is because when the carbon emission cap $T \ge T^G$, the carbon emission standard is relatively relaxed, and thus, the manufacturer can maximize his profits.

On the other hand, when the carbon emission cap is below the threshold T^G (i.e., $T < T^G$), the manufacturer's optimal production quantity becomes proportional to the carbon emission cap. This is because when the government tightens its green restrictions, the manufacturer cannot set his production quantity as the extreme point value. He has to set it as the upper boundary to earn as much profit as possible subject to the carbon emission cap.

Lemma 1 provides the optimal response function of the production quantity to the wholesale price. We next turn to the supplier's optimal decisions.

The supplier's problem can be formulated as

$$\pi_s^G = (w^G - c)q^G,$$

Similarly, we are able to obtain her optimal decision in Lemma 2:

Lemma 2. Under the GCF mode, the optimal equilibrium solutions of the supplier are satisfied as follows:

when $T \geq T^G$, $w^{G*} = \dfrac{pq^{G*} f(\hat{y}^G)}{1+R} + c$ and

when $T < T^G$, $w^{G*} = \bar{w}$,

where $\hat{y}^G = q^{G*} - A - \delta\sqrt{K_t}$ means the threshold of zero cash flow and $\bar{w}$ means the upper boundary of the wholesale price, where $\bar{w} = p/(1+R)$. The proof is in the Appendix.

As shown in Lemma 2, when $T \geq T^G$ (i.e., the carbon emission cap is relatively relaxed), the supplier can set the optimal wholesale price $w^{G*} = pq^{G*} f(\hat{y}^G)/(1+R) + c$ to maximize her expected profits. When $T < T^G$, as long as the manufacturer continues to participate, the supplier has the incentive to raise her wholesale price to the upper limit. This is because we assume that the manufacturer is a long-running and creditworthy company. In case the manufacturer's income is not enough to cover his repayment, we assume that he will continue operating the business with negative cash flow by fully repaying the loan. Considering that the manufacturer is a Pareto or a good-willed participant, he will stay in the game. Similar conclusions are consistent with Jing, Chen, & Cai (2012) and have widely discussed in other literature (e.g., Chen, 2015; Li, An, & Song, 2018; Zhan, Chen, & Hu, 2019). The implication is that the supplier takes most of the profits from the manufacturer under the LCE condition. This is because when the carbon emission cap is relatively restricted, the manufacturer faces a strict carbon emission requirement. Thus, his production quantity is limited and can reach the maximum value only within the carbon emission standard. As a result, the manufacturer's production might not be able to satisfy the demand, and thus, he faces a great risk of out of stock, which may result in the manufacturer's failure to repay the loan. As a result, to protect her interests, the supplier has the incentive to increase her wholesale price to the upper limit.

To analyze the influence of green investment on the equilibrium, we consider the following proposition.

Proposition 1. Given that GCF is viable, （1） $\dfrac{dq^{G*}}{dK_t} > 0$ regardless of T;

（2） $\dfrac{dw^{G*}}{dK_t} > 0$ under the $T \geq T^G$ condition, but the optimal wholesale price is irrelevant to the green investment K_t under the $T < T^G$ condition.

The proof is in the Appendix.

Proposition 1 is relatively intuitive, given the $T \geq T^G$ condition, since the green investment boosts demand for the product, which encourages an increase in the manufacturer's production quantity. Meanwhile, the supplier would like to increase her wholesale price to obtain a higher profit. While under the $T < T^G$ condition, since the total amount of carbon emissions is more strictly constrained, the manufacturer is limited in his production to reduce total carbon emissions. The increase in green investment can reduce the environmental impact of production, then the decrease in the environmental impact can promote higher demand and encourage an increase in production. Thus, when total carbon emissions are limited, the increase in green investment can increase the production quantity. Besides, when given a strict carbon emission constraint, the supplier's optimal wholesale price is irrelevant to the manufacturer's green investment.

3.3 Trade credit financing mode

In this subsection, we consider the case of using TCF to solve the capital constraint problem when a firm commits to green investment. The initial capital of the manufacturer can cover his green investment ($K \geq K_t$). After the green investment, the remaining capital is not enough for the manufacturer to finance his production, so the manufacturer applies a trade credit finance (deferred payment service) from the supplier (Chen, 2015). The trade credit financing that the manufacturer applies to the supplier here is a financing without advance payment. The simplest definition of trade credit is an arrangement to purchase goods and/or services on account without paying cash upfront but paying the supplier at a later scheduled date. (https://www.investopedia.com/terms/t/trade-credit.asp). Since trade credit puts suppliers at a certain disadvantage, many suppliers use discounts to encourage early payment when it comes to trade credit. If the buyer pays within a certain number of days before the due date, the supplier can give a discount. Our paper does not consider the accounting period, so we do not consider the issue of early payment. We assume that the manufacturer has obtained a trade credit without initial payment, that is, the supplier provides goods to the manufacturer at the beginning of the period, and the manufacturer repays the supplier at the end of the period, the loan is $w^T q^T$, thus, the repayment at the end of the period is $w^T q^T$. This assumption has been adopted in the literature, e.g. Chen (2015); Jing, Chen, & Cai (2012); Rui & Lai (2015). We describe the sequence of events as follows. First, the supplier publishes her wholesale price w^T, where $w^T = w(1+R_s)$ is defined as the postponed wholesale price at the end of the period under TCF.

Second, the manufacturer decides his production quantity q^T and undertakes green investment K_t. After the green investment, the remaining capital $K - K_t$ is not enough for performing production, thus the manufacturer seeks trade credit financing service from the supplier for delayed payment of the assets $w^T q^T$ to execute his production quantity. Third, after the demand is realized, the manufacturer receives his revenue $E[p\min\{D,q^T\}]$ and repays his loan $w^T q^T$ to the supplier. In case the manufacturer's income is not enough to cover his repayment, we assume that he will continue operating the business with negative cash flow by fully repaying the loan. If the manufacturer's carbon emissions exceed the government-defined threshold, then he incurs a penalty in proportion to the excessive emissions. Clearly, if the parameter c_e is sufficiently large, the carbon emission constraint tends to be a hard constraint.

The expected end-period cash flow of the manufacturer is given as follows:

$$E[\pi_m^T(q^T)] = E[p\min\{D,q^T\}] - w^T q^T + K - K_t - c_e[(t - \theta K_t)q^T - T]^+ .$$

Using the backward method, the optimal reaction function of production quantity is summarized in Lemma 3.

Lemma 3. Under TCF mode, given a wholesale price w^T by the supplier, the manufacturer's optimal production quantity is

$$q^{T*} = \begin{cases} F^{-1}\left(\dfrac{p - w^T}{p}\right) + A + \delta\sqrt{K_t}, & T \geq T_1^T \\ \dfrac{T}{t - \theta K_t}, & T_2^T \leq T < T_1^T \\ F^{-1}\left(\dfrac{p - w^T - c_e(t - \theta K_t)}{p}\right) + A + \delta\sqrt{K_t}, & T < T_2^T \end{cases},$$

where $T_1^T = (t - \theta K_t)[F^{-1}(\dfrac{p - w^T}{p}) + A + \delta\sqrt{K_t}]$ and $T_2^T = (t - \theta K_t)[F^{-1}(\dfrac{p - w^T - c_e(t - \theta K_t)}{p}) + A + \delta\sqrt{K_t}]$.

The proof is in the Appendix.

From Lemma 3, we observe that the optimal production quantity under TCF can be determined by three types of strategies according to the value of the carbon emission cap. Depending on the different carbon emission caps set by the government, the manufacturer's optimal production quantity response is also different. When $T \geq T_1^T$, the carbon emission cap is relatively relaxed, we call it under HCE condition; and when $T < T_2^T$, the carbon emission cap is relatively tight, we call it under LCE condition. When $T_2^T \leq T < T_1^T$, we call it under medium condition. It can be seen that if the government sets the carbon emission cap relatively large or relatively small, the manufacturer's optimal production quantity would be at the extreme point value. On the other hand, if the carbon emission cap is set in the range of (T_2^T, T_1^T), the manufacturer's optimal production quantity would be at the boundary value imposed by the carbon emission cap. This phenomenon enlightens the manufacturer to make his own optimal production plan according to the emission cap set by the government.

Moreover, the supplier's end-period cash flow in TCF mode is

$$\pi_s^T = w^T q^T - cq^T .$$

Thus, we obtain Lemma 4.

Lemma 4. Under TCF mode, the optimal equilibrium solution of the supplier's decision is given by $w^{T*} = \begin{cases} p, & T_2^T \leq T < T_1^T \\ pq^{T*} f(\hat{y}^T) + c, & otherwise \end{cases}$, where $\hat{y}^T = q^{T*} - A - \delta\sqrt{K_t}$, T_1^T and T_2^T are given in Lemma 3.

The proof is similar to that for Lemma 2.

From Lemma 4, if the carbon emission cap set by the government is relatively large or relatively small, the supplier can set her wholesale price to be the extreme point value to maximize her profits. However, if the carbon emission cap is in the middle region, the supplier will choose the upper limit of the price. This is because the manufacturer's optimal order quantity is independent of the supplier's wholesale price (from Lemma 3), and the uncontrollability of the manufacturer brings great risk to the supplier; thus, the supplier will set her wholesale price to the upper limit to maximize her profit.

Obviously, it is worthwhile to point out that the carbon emission threshold values under the GCF and TCF cases are different. In fact, we have the following result:

Proposition 2. Comparing the thresholds of the carbon emission cap under GCF and TCF modes, we have (1) $T^G < T_1^T$; (2) $T_2^T < T_1^T$; (3) $T^G \geq T_2^T$ for $R \leq \frac{c_e(\tau - \theta K_t)}{c}$; $T^G < T_2^T$ for $R > \frac{c_e(\tau - \theta K_t)}{c}$.

The proof is in the Appendix.

From Proposition 2, we observe the relationship of the threshold values of the carbon emission under GCF and TCF. Note that this threshold value is the actual carbon emission of the manufacturer, which determines whether the enterprises are constrained (punished) by carbon emissions cap under GCF and TCF respectively. T^G is the actual carbon emissions under GCF, T_1^T is the actual carbon emissions under the TCF without penalty, and T_2^T is the actual carbon emissions under TCF with the penalty.

Firstly, from Proposition 2 (1) we know $T^G < T_1^T$, which means the emissions of the manufacturer under GCF are lower than those without penalty under TCF. This phenomenon illustrates the effectiveness of GCF. The aim of the green credit is to enforce strict requirements of carbon emissions, support companies for the green economy, low-carbon economy, and circular economy, and encourage banking financial institutions to cooperate with the implementation of the national energy conservation and emission reduction strategy. In addition, many studies on green credit have indicated that the purpose of green credit is to promote energy conservation and emission reduction in the development of enterprises (e.g., Thompson & Cowton (2004); Xiu, Liu, & Zang, 2015). Our observations demonstrate the effectiveness of GCF.

Proposition 2 (2) $T_2^T < T_1^T$ shows that the carbon emission constraint policy is effective in promoting carbon emission reduction, the punishment measures can effectively reduce the carbon emissions of the company (Hammami, Nouira, & Frein, 2015; Choudhary, Sarkar, Settur, & Tiwari, 2015).

Proposition 2 (3) compares the carbon emission reduction effectiveness of GCF and TCF with the carbon emission penalty. It can be seen that the result depends on the interest rate under GCF. When the interest rate is relatively low, the carbon emission under GCF is higher. In other words, in order to effectively reduce carbon emissions, it would be helpful to appropriately increase the interest rate. By increasing the interest rate on polluting enterprises, banks are able to regulate the capital flow of enterprises with credit resources, accelerate the upgrading of green industrial structure, and finally promote the green transformation and sustainable development of polluting enterprises(Xu & Li, 2020; He, Zhang, Zhong, Wang, & Wang, 2019).

In short, Proposition 2 implies that the carbon emissions under GCF and TCF with carbon penalty are lower than those without punishment under TCF, which shows the effectiveness of carbon emission reduction measures. Furthermore, although GCF is a kind of credit service to urge enterprises to carry out green emission reduction, in order to achieve more carbon emission reduction, GCF needs to appropriately increase its credit interest rate.

4. Equilibrium between different financing modes

In the previous section, we characterize the equilibrium solutions for the supply chain members under GCF and TCF. Next, we compare the situation in which there is no carbon emission constraint with GCF and TCF. We also consider which option is better for the supplier and for the manufacturer when both financing methods are available.

4.1 Comparison under carbon emission constraint and no constraint

Using the case with no carbon emission constraint as a benchmark, the equilibriums are the same as those in the HCE condition under GCF and TCF. We denote this scenario without the constraint using the superscripts ^{GB} and ^{TB}, and the situation with the carbon emission constraint using the superscripts ^{GL} and ^{TL} under GCF and TCF, respectively. Comparing the equilibriums with and without carbon constraints, we have the following proposition.

Proposition 3. Comparing the cases with carbon emission constraint and without carbon constraint,

(1) Under GCF, we have the optimal wholesale price satisfies $w^{GB*} \leq w^{GL*}$ and the optimal production quantity satisfies $q^{GB*} \geq q^{GL*}$;

(2) Under TCF, when given the HCE condition, we have $w^{TB*} = w^{TL*}$; when given medium condition($T_2^T \leq T < T_1^T$), we have $w^{TB*} < w^{TL*}$; when given LCE condition, there exists a penalty of unit excessive carbon emissions threshold point $\hat{c}_e$ such that $w^{TB*} > w^{TL*}$ if $c_e > \hat{c}_e$, $w^{TB*} \leq w^{TL*}$ if $c_e \leq \hat{c}_e$, where $\hat{c}_e = \dfrac{p\bar{F}(\hat{y}^{TB*}) - p\bar{F}(\hat{y}^{TL*})}{\tau - \theta K_t}$; and the optimal production quantity satisfies $q^{TB*} \geq q^{TL*}$.

where w^{GB} (w^{TB}) refers to the wholesale price with no carbon emission constraint under GCF (TCF) and w^{GL} (w^{TL})refers to the wholesale price with carbon emission constraint of GCF (TCF); the same applies to the production quantities. The proof is in the Appendix.

From Proposition 3 (1), we observe that $w^{GB*} \leq w^{GL*}$. This result may be explained as follows. Under the LCE condition, the carbon emission cap set by the government is relatively low. If the manufacturer's emission output exceeds the cap, the bank will withdraw the green credit. Therefore, the manufacturer has to choose the boundary production quantity. This production quantity is independent of the supplier's wholesale price. In addition, once the manufacturer's emission output exceeds the cap, the manufacturer's capital chain will be broken, which will eventually lead to termination of the supply chain. This brings great risks to the upstream supplier. Therefore, in order to reduce her own risks, the supplier tends to increase the wholesale price to the upper bound to ensure her own interests. With regard to the comparison of the production quantities without carbon emission constraint and with constraint under GCF, we have $q^{GB*} \geq q^{GL*}$. This phenomenon shows that green credit under the LCE condition can restrict the output of the enterprises. This result is consistent with the findings in the literature indicating that green credit policy could restrain the output of the polluting enterprises in a range of industries such as the papermaking industry, chemical industry, agriculture, light industry, and service industry(Liu, Xia, Fan, Lin, & Wu, 2017).

With regard to the results of TCF in Proposition 3 (2), under HCE condition, the government has set a relatively high carbon emission cap, and the carbon emission requirements are relatively loose, which essentially becomes the same as the case of no carbon emission constraint. Therefore, the optimal production quantities and wholesale prices are equal in both cases. When the carbon emission policy is slightly tightened, the output of the manufacturer will also be tightened to the boundary value constrained by the emission cap. At this point, the supplier will increase her wholesale price to the upper limit in order to maximize her own revenue. When the carbon emission policy continues to tighten, the manufacturer has to face the emission penalty and chooses the output that maximizes his profit under the punishment. Due to the impact of carbon emission penalties, the output of the manufacturer is lower than that under the unconstrained condition. At this time, the supplier's wholesale price depends on the government's punishment coefficient. If the punishment is strong

($c_e > \hat{c}_e$), the supplier's optimal wholesale price under the penalty will be lower than the unconstrained wholesale price. This is because a larger penalty will reduce the manufacturer's output, and the supplier acts not only as an operator but also participates as a financier. She shoulders the risk of the manufacturer, thus she will reduce her wholesale price to encourage the manufacturer to increase his output; and when the penalty is lighter ($c_e \le \hat{c}_e$), the supplier would like to increase her wholesale price to capture more profits.

4.2 Comparison under GCF and TCF

We next compare the equilibrium solutions under GCF and TCF.

Proposition 4. Comparing the supplier's wholesale prices and the manufacturer's optimal production quantities under GCF and TCF, we have:

(1) For any given carbon emission cap *T*, we have $q^{G*} \le q^{T*}$;

(2) Under HCE (LCE) condition, there exists an interest rate threshold $\hat{R}_1$ ($\hat{R}_2$), if $R < \hat{R}_1$ ($\hat{R}_2$), we have $w^{G*} > w^{T*}$; otherwise, we have $w^{G*} \leq w^{T*}$, where $\hat{R}_1 = \frac{\bar{F}(\hat{y}^{G^*})}{\bar{F}(\hat{y}^{T*})} - 1$, $\hat{R}_2 = \frac{p}{p\bar{F}(\hat{y}^{T*}) - c_e(t - \theta K_t)} - 1$; Under medium condition($\min\{T^G, T_2^T\} \le T < T_1^T$), if $R_0 \le R < \hat{R}_3$, we have $w^{G*} > w^{T*}$, otherwise we have $w^{G*} \le w^{T*}$. Here, $R_0 = \frac{c_e(t - \theta K_t)}{c}$, $\hat{R}_3 = \frac{p\bar{F}(\hat{y}^{G*})}{p\bar{F}(\hat{y}^{T*}) - c_e(t - \theta K_t)} - 1$.

The proof is in the Appendix.

Proposition 4 (1) compares the optimal production quantities under the two financial modes. It shows that regardless of the level of carbon emission cap set by the government, the manufacturer's output under TCF is always greater than that under GCF. This may be interpreted from two aspects. On the one hand, because the supplier bears part of the manufacturer's risk under TCF, the supplier may reduce the wholesale price to some degree under certain conditions to stimulate the manufacturer to increase production; on the other hand, the hard constraint under GCF is obviously more stringent than the penalty of carbon emission excess under TCF. Therefore, the combined effect results in lower manufacturer output under GCF than under TCF. The managerial insight of Proposition 4(1) is that GCF is more effective than TCF to restrain the output of enterprises.

Proposition 4 (2) compares the optimal wholesale prices between two financial modes. Under both HCE ($T \ge T_1^T$) and LCE ($T < \min\{T^G, T_2^T\}$) condition, when the bank's interest rate is relatively low, the manufacturer's financing cost will be reduced and his optimal production quantity will be increased under GCF. Therefore, the supplier tends to set a higher wholesale price to grab more profits. This explains the higher wholesale price under GCF than under TCF. When the carbon emission cap set by the government is located in the middle region($\min\{T^G, T_2^T\} \le T < T_1^T$), but the bank's interest rate satisfies $R_0 \le R < \hat{R}_3$, for the same reason as above, the wholesale price of the supplier under GCF is higher than that under TCF. However, it is surprising that when the bank's interest rate continues to fall ($R < R_0$), we have $w^{G*} \le w^{T*}$. This may be interpreted as follows. Recalling that in Proposition 2, when the interest rate is relatively low ($R < R_0$), the threshold of carbon emission constraint under GCF is higher than that under TCF ($T^G > T_2^T$). The carbon emission cap set by the government is $T > T^G > T_2^T$. Under such condition, the manufacturer can only choose the boundary value of penalty under TCF, and this production quantity is the maximum quantity that the manufacturer can choose under such condition, which is independent of the wholesale price of the supplier. Recalling that the supplier acts as a vendor as well as a financier under TCF, and the uncontrollability of the manufacturer's decision brings greater risk to the supplier. The supplier will set her wholesale price to the upper limit to protect her own interests. Therefore, we have $w^{G*} \le w^{T*}$. Proposition 4(2) implies that the relationship of the optimal wholesale prices between two financing modes can be nicely characterized by the parameters *T* and *R* in relation to HCE, LCE, and medium condition.

Proposition 5. Under the HCE condition, TCF is the subgame perfect financing equilibrium of the supplier.

The proof is in the Appendix.

Proposition 5 indicates that the supplier's potential gain under TCF exceeds that under GCF when given HCE condition. Under such loose carbon emission policy, the supplier can set a wholesale price as her optimal value under TCF and set a higher one under BCF to induce the manufacturer to choose TCF when both financing modes are viable.

5. Numerical results

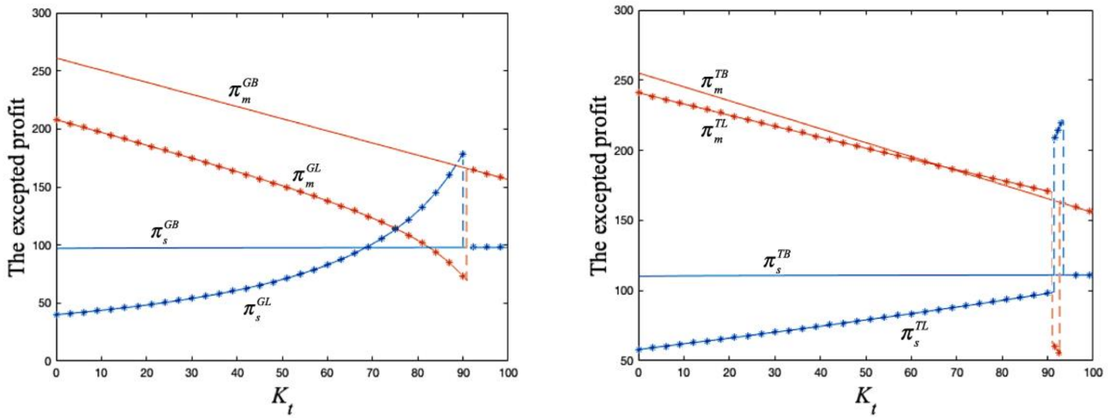
In this section, we conduct numerical analysis to further analyze the influences of some key parameters and gain insights comparing the optimal profits with and without carbon emission constraints between the GCF and TCF modes. In order to make numerical experiments more convincing, we use real-world data to do numerical experiments. We selected a power generation company in China, which choose to invest in carbon capture and storage (CCS) technology to reduce the carbon emission level. The data below are based on China Energy Statistical Yearbooks, China Statistical Yearbooks, and some other research about the investment of CCS technology (Zhu & Fan, 2011). The data is as follows.

The average industrial electricity price of power plants in 2007 was 0.69 yuan/kWh, the production cost per unit was 0.3 yuan/kWh and the risk-free rate was 5.00%. The excessive carbon emission penalty cost was 0.12 yuan/kWh, the initial capital was 200 million yuan/year, the green input cost was 100 million yuan/year, the carbon emission without CCS technology was 0.893×103g CO_2/kWh, and the per-unit carbon emission reduction after green improvement was 0.077×103g CO_2/kWh. We set the carbon emission cap as 100g CO_2/kWh. Assume that demand follows a uniform distribution with a mean value of 1000 (Cai et al., 2014)， the basic market demand was 0 (Chemama, Cohen, Lobel, & Perakis, 2019) and we suppose that the per-unit demand increasing from the green investment is 0.5. Since the two parameters K_t and T influence the results most. We analyze their impact on chain members' optimal expected end-period cash flow.

5.1 Comparative analyses with and without carbon emission constraints

We undertake numerical studies to compare the expected profits of the manufacturer and supplier disrupted by the manufacturer's green investment K_t under GCF. It should be noted that for a given carbon emission cap *T*, the HCE (LCE) condition would limit the value range of the green input K_t. For example, when $T = 100$, the HCE condition ($T^G \le T$) would require K_t being greater than 92.1893; and the LCE condition would require K_t being less than 92.1893. In Fig. 1(a), the red lines refer to the manufacturer and the blue lines to the supplier. We observe that it is beneficial for the manufacturer to be unconstrained (p_m^{GB}) when given LEC condition. This is because, in the case of LCE, the manufacturer may face the risk of not obtaining a bank loan under the strict carbon emission policy. To avoid the risk of supply disruption, the supplier sets a higher wholesale price to capture lots of the manufacturer's revenue.

We next compare the supplier's profit under GCF (blue lines in Fig. 1(a)). we can see the relationship between the supplier's profit of the two cases is related to the green investment of the manufacturer when given LEC condition. The supplier sets a lower wholesale price without restriction ($w^{GB*} \le w^{GL*}$)， which results in a higher production quantity ($q^{GB*} \ge q^{GL*}$). With a relatively low green investment, the profit of the supplier without restriction is higher than that under LCE. This indicates that the effect of the production quantity on the supplier's profit exceeds that of the wholesale price. With the increase of green investment (K_t), the production quantity in both cases will increase, but the green input stimulates LCE more than that of the unconstrained case, so the supplier's profit under LCE is larger. This suggests that the supplier can give in partial profit to stimulate sales to effectively improve corporate profits.



(a) Under GCF (b) Under TCF

Fig. 1 Expected profits of the manufacturer and supplier disrupted by K_t under GCF and TCF

The profit of the manufacturer under TCF is different from that under GCF, as shown in Fig. 1(b). The profit of the manufacturer is no longer always high under the easing policy (p_m^{TB} in Fig. 1(b)), as it is related to his green investment when given LEC condition. When the green investment is low, the profit of the manufacturer is high without the carbon emission punishment constraint; when the green investment is high, the profit with constraint is high. This suggests that the government can set a stringent carbon emission penalty policy to stimulate the firm's green investment, and it is interesting to find that this policy is also profitable for the company.

Under TCF, the situation of suppliers is different from that under GCF. The supplier has a high profit in a relaxed environment (p_s^{TB} in Fig. 1(b)) when given LEC condition. Because the supplier and manufacturer form an alliance this time, the supplier not only acts as an operator but also participates as a financier in the game. A strict carbon emissions policy results in a lower profit of p_s^{TL} . Similarly, the supplier's profit is high under the loose policy. It should be noted that when under medium condition(91.7043< K_t <93.0946), the profit of the supplier is much higher than that of the manufacturer because the supplier can set a rather high wholesale price to capture most of the manufacturer's profit. This observation is consistent with Lemma 4.

5.2 Comparative analyses between GCF and TCF

In this subsection, we compare the strategic interplay between the supplier and manufacturer when both GCF and TCF are available (Figs. 2 and 3), that is, we compare the expected end-period cash flow between the GCF and TCF modes. In Fig. 2, the red line refers to the GCF mode, and the blue line the TCF mode. Note that the region between T_2^T and T_1^T is very small, which appears to have rather limited research value. Thus, we choose to concentrate our attention on those more likely scenarios to obtain meaningful managerial insights.

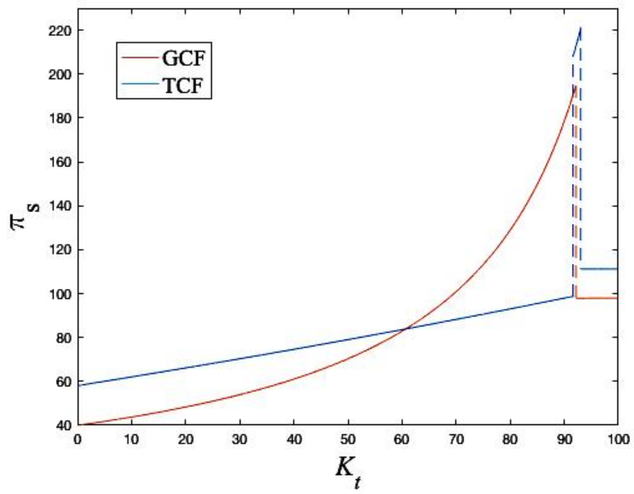


Fig. 2 Profit of the supplier disrupted by K_t under GCF and TCF

It should be noted that K_t < 92.1893 refers to LCE condition under GCF, and K_t <91.7043 refers to LCE condition under TCF, and K_t >93.0946 refers to the HCE condition under TCF. On the one hand, under the LCE condition (K_t <91.7043) from Fig. 2, we observe that the supplier's choice depends on the manufacturer's green investment. Only with strict green investment is the supplier better off with TCF. The phenomenon behind this is that when the carbon emission cap is low enough, it signals that the environmental policy has been tightened. We observe that when the manufacturer's green investment is relatively low, both the production quantity and the wholesale price under GCF are lower than those under TCF, thus, the supplier prefers TCF over GCF. While when the green investment is higher than the threshold, though the production quantity under GCF is still lower than that under TCF, the wholesale price is higher under GCF, which results in a higher profit of the supplier under GCF. This shows that the impact of the wholesale price on the supplier's profit exceeds that of the production, which inspires the supplier should appropriately increase her wholesale price to increase the marginal revenue under certain conditions.

On the other hand, under the HCE condition (K_t >93.0946) from Fig. 2， we observe that the supplier's profit is higher under TCF then that of GCF, which is consistent with Proposition 5. This is because under HCE condition, neither carbon emission constraint nor punishment worked, the supplier enjoys integration of finances and operations, and has full control of her trade credit interest rate and wholesale price. By delaying payments to the supplier, the manufacturer can exert effort to improve his production quantity. This is why in practice suppliers are willing to provide manufacturers with deferred payment, which is consistent with Kouvelis & Zhao (2012) and Chen (2015).

Next, we discuss the optimal end-period cash flow of the manufacturer under the two financing modes. Given the LCE condition(K_t <91.7043), the supplier sets her optimal wholesale price as the upper bound to avoid the manufacturer's risk of exceeding the carbon emission cap and seizes most of the manufacturer's profit under GCF. As the intuition suggests, TCF is preferred by the manufacturer over GCF, which is consistent with our observation. Given the HCE condition, there is a higher production quantity but also a higher wholesale price under TCF than under GCF. The difference between the production quantities is smaller than that between the wholesale prices. The manufacturer's additional gain cannot offset his potential loss due to the higher wholesale price under TCF. As a result, GCF is the manufacturer's preferred choice (Fig. 3).

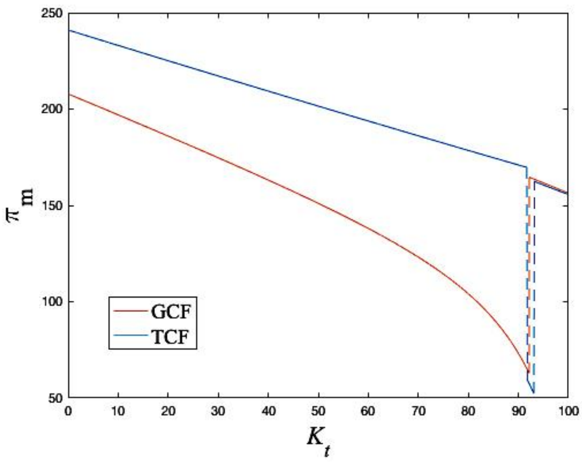


Fig. 3 Profit of the manufacturer disrupted by K_t under HCE condition

Consequently, under the LCE condition, if the carbon emission cap is relatively low, given a relatively lower green investment by the manufacturer, the supplier is better off under TCF, and recall that the manufacturer also prefers TCF. Therefore, TCF is the sub-game perfect financing equilibrium under such a condition. Meanwhile, TCF results in higher channel integration, since production financing relies on the supplier, which reduces the efficiency loss caused by double marginalization. As a result, with a strict carbon emission policy, the chain members can negotiate the manufacturer's green investment to obtain a win-win situation. On the contrary, given the HCE condition, the supplier and the manufacturer have a conflicting choice. The supplier prefers TCF while the manufacturer prefers GCF.

6. Comparative analysis of social welfare

Up to now, we have characterized the financing performance under the two financing modes. Next, we compare social welfare under the modes. According to Krass, Nedorezoy, & Ovchinniov (2013), we define social welfare as

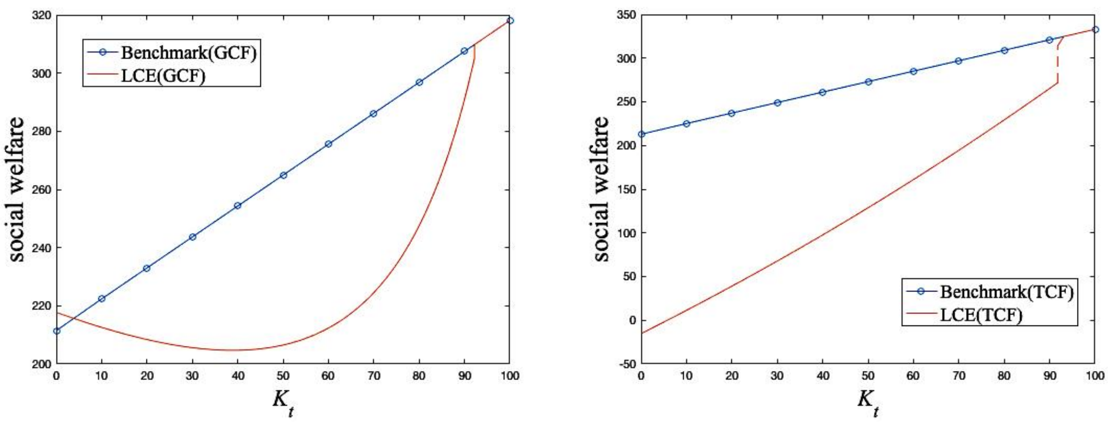
Social Welfare = Firm's Profit + Consumer Surplus - Environmental Impact.

Consumer surplus is an economic indicator for calculating consumer satisfaction, which analyzes the area between the demand curve and the given price (Cohen, Lobel & Perakis, 2016). In our study, demand is stochastic, and customers may suffer a welfare loss through stockout, in which consumer surplus is represented as follows (Raz & Ovchinnikov, 2015; Chemama, Cohen, Lobel, & Perakis, 2019):

$$CS_{\max} = \frac{(D - A)^3}{3d^2}; \ CS_{stochastics} = CS_{\max} \times \frac{\min\{D, q\}}{D}.$$

We note that green investment can improve the impact on the environment, and following Bi, Jin, Ling, & Yang (2016) and Raz, Druehl, &Blass (2013), we define the environmental impact as $h(t - qK_t)q$, where t is the initial cap emissions of the manufacturer. q is production quantity, q is the environmental improvement degree of green investment, and h is the unit environmental impact level， $m \in [0,1]$ is the proportion of socially responsible manufacturer concerned (Sinayi & Rasti-barzoki, 2018). Therefore, social welfare can be defined as

$$SW = p_m + p_s + mCS - h(t - qK_t)q$$



(a) under GCF (b) under TCF

Fig. 4 Social welfare disrupted by K_t

We consider the impacts of carbon emission constraints on social welfare under GCF, as shown in Fig. 4 (a), where $h = 0.5$, $m = 10^{-7}$. To our surprise, the social welfares under the constraint of carbon emissions are lower than that without carbon emissions within a moderate region of K_t. This phenomenon indicates that although there are constraints on the carbon emissions of enterprises under LCE, and with the increase of green investment, it will reduce the environmental impact and improve the consumer surplus. However, carbon emission constraint may limit the output of the industries because carbon emission reduction policies have a significant negative impact on the economic output of some regions (Hassler & Krusell, 2012) and will lead to a certain degree of decline in the output of various industries(Zhang, 2019). As a result, the overall profits of the supply chain may decrease. Obviously, when the positive impact on the environment and consumer surplus is lower than the negative impact on the supply chain profits, the social welfare under LCE will be lower than that without emission constraint. This observation is consistent with the findings in the literature. For example, Ning & She (2014) stated that green credit has a negative impact on macroeconomic development, and Xiu, Liu, & Zang (2015) found that green credit policies may curb relatively inefficient energy-intensive industries and affect the industrial restructuring in the long run. All of these effects will cause a decrease in social welfare.

At the same time, we can also see that when the green input is relatively low, the social welfare under GCF is higher than that without constraint (Benchmark). This is because when the green investment cost is low, which will lead to a high overall profit of the supply chain, resulting in higher social welfare.

When refers to TCF, from Fig 4 (b), we can see that the social welfare under LCE is also lower than that without punishment (Benchmark). This is because in addition to limiting the output under LCE, carbon emission punishment also increases the cost, which leads to the decline of social welfare(Leach, 2009; Pindyck, 2012; Chen & Nie, 2016; Tan, Xiao, & Zhou, 2019).

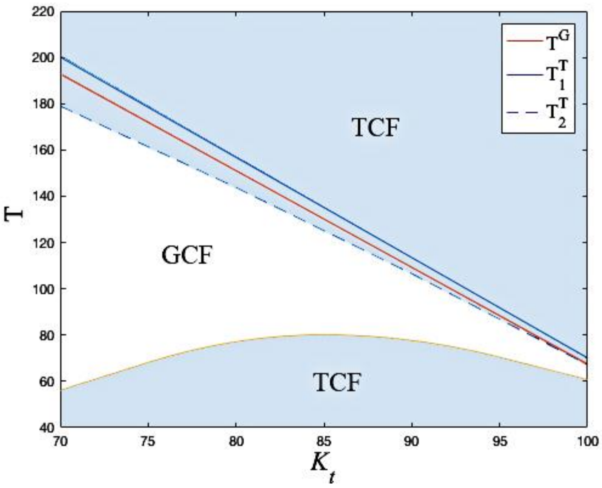
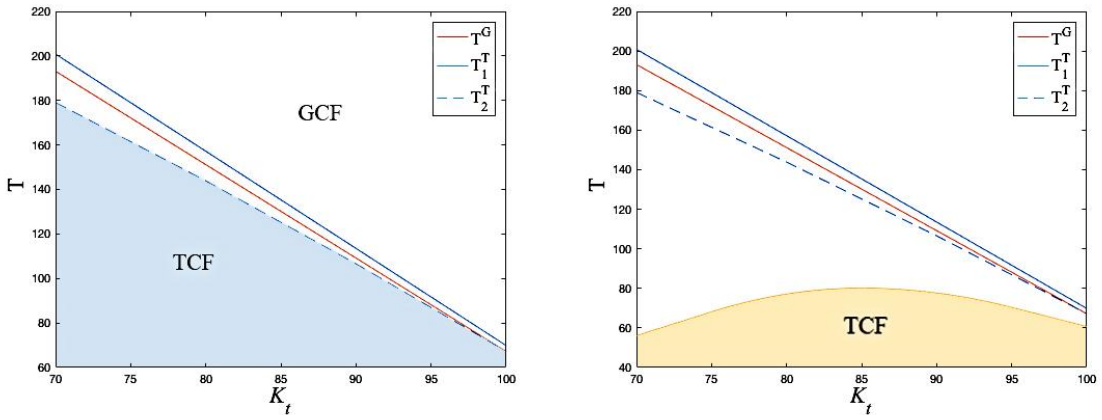


Fig. 5 Social welfare comparison between GCF and TCF

Next, we compare social welfare under GCF and TCF with the combination of (K_t, T). In Fig. 5, the shaded part is the region with higher social welfare under TCF, and the white part is that with a higher social welfare region under GCF. It is evident that the region under the TCF mode is larger, which shows that the conditions for achieving better social welfare under TCF are more relaxed. Under the HCE condition, the government can induce enterprises to choose TCF to maximize social welfare by raising the green credit rate. Under the LCE condition, the government should induce enterprises to choose the maximum social welfare financing method according to the upper limit of carbon emissions. When in the middle region $T_2^T \le T < T_1^T$, Fig. 5 shows that the carbon emission thresholds of the two financing methods are very close, the social welfare under TCF is higher than that under GCF. This is because the wholesale price and production quantity are all higher under TCF than those under GCF in this region, which results in a higher profit of the supplier and consumer surplus.



(a)From the viewpoint of the manufacturer (b) From the viewpoint of social welfare and the manufacturer

Fig. 6 Comparison of GCF and TCF modes

From the viewpoint of the manufacturer, as seen in Fig. 6(a), under a loose carbon emission policy, he has higher profits under GCF. Under a strict carbon emission policy, his profits are higher under TCF. This is because when the manufacturer’s carbon emission performance does not meet the standard, he is exposed to the risk of not receiving GCF. In such a situation, the supplier sets a higher wholesale price to capture the most profits of the manufacturer. Therefore, under strict carbon emission policies, choosing TCF (and sharing operational and financing risks with the supplier) is a better option for the manufacturer than GCF.

An interesting question is whether a situation exists in which both social welfare and the manufacturer’s profit can be maximized. As Fig. 6(b) shows, the shaded region is this in which both the manufacturer and the government can reach an agreement and maximize their utility. The implication is that the government can guide the manufacturer to make a win-win choice by setting appropriate carbon caps. Specifically, when the government sets a strict carbon cap, that is, under a strict carbon policy, if the manufacturer chooses TCF financing, his profit and the social benefits can be maximized, which corresponds to the shaded region.

7. Extension

In this section, we extend the model to the case where both the production quantity and green investment are the decision variables for the manufacturer. The sequence of events is the same as mentioned before, except that the manufacturer decides the production quantity and green investment simultaneously. Using the backward method, the optimal reaction function of production quantity is summarized in Lemma 5.

Lemma 5. When given a wholesale price by the supplier, the manufacturer’s end-period cash flow is joint concave in the production quantity and the green investment. The manufacturer’s optimal decisions under GCF and TCF are as follows:

$$q^{G*}=\begin{cases} F^{-1}\left(\dfrac{p-w^{G}(1+R)}{p}\right)+A+\delta\sqrt{K_t^{G^*}}, & T\geq T^{G}\\ \dfrac{T}{t-\theta K_t^{G^*}}, & T<T^{G}\end{cases}$$

, and $K_t^{G^*}$ satisfies

$$\begin{cases} \dfrac{\delta p}{2\sqrt{K_t^{G^*}}}F(\hat{y}^{G^*})-(1+R)=0, & T\geq T^{G}\\ \theta q^{G^*}[p\bar{F}(\hat{y}^{G^*})-w^{G}(1+R)]-(t-\theta K_t^{G^*})[-\dfrac{\delta p}{2\sqrt{K_t^{G^*}}}F(\hat{y}^{G^*})+(1+R)]=0, & T<T^{G}\end{cases},$$

where $T^{G}=(t-\theta K_t^{G^*})[F^{-1}(\dfrac{p-w^{G}(1+R)}{p})+A+\delta\sqrt{K_t^{G^*}}]$, $\hat{y}^{G^*}=q^{G^*}-A-\delta\sqrt{K_t^{G^*}}$.

Only when $\delta pK_t^{T^*-\frac{1}{2}}f(\hat{y}^{T^*})[\dfrac{p}{4}K_t^{T^*-1}F(\hat{y}^{T^*})-c_e\theta]-c_e^{2}\theta^{2}>0$, we have

$$q^{T*}=\begin{cases} F^{-1}\left(\dfrac{p-w^{T}}{p}\right)+A+\delta\sqrt{K_t^{T^*}}, & T>T_1^{T}\\ \dfrac{T}{t-\theta K_t^{T^*}}, & T_2^{T}\leq T\leq T_1^{T}\\ F^{-1}\left(\dfrac{p-w^{T}-c_e(t-\theta K_t^{T^*})}{p}\right)+A+\delta\sqrt{K_t^{T^*}}, & T<T_2^{T}\end{cases}$$

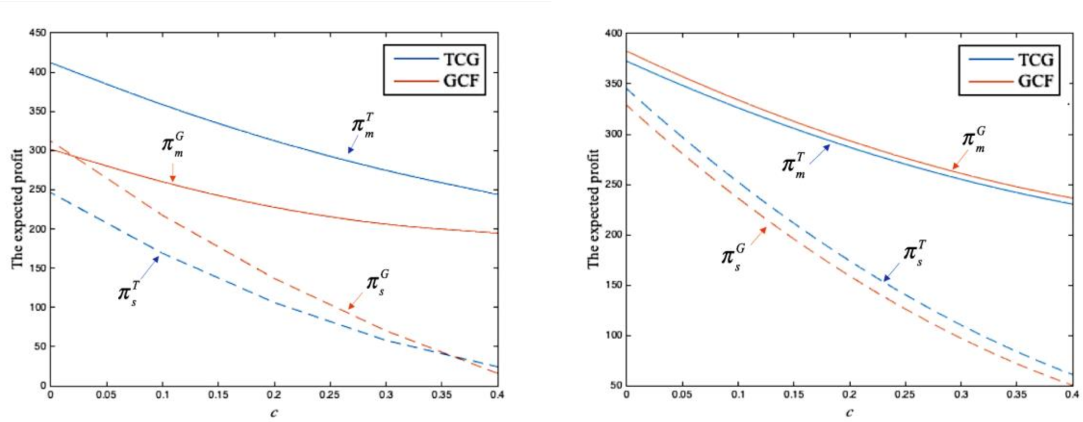
, and $K_t^{T^*}$ satisfies

$$\begin{cases} \dfrac{\delta p}{2\sqrt{K_t^{T^*}}} F(\hat{y}^{T^*}) - 1 = 0, & T \geq T_1^T \\ \theta q^{T^*}[p\bar{F}(\hat{y}^{T^*}) - w^T] - (t - \theta K_t^{T^*})[1 - \dfrac{\delta p}{2\sqrt{K_t^{T^*}}} F(\hat{y}^{T^*})] = 0, & T_2^T \leq T < T_1^T \\ \dfrac{\delta p}{2\sqrt{K_t^{T^*}}} F(\hat{y}^{T^*}) - 1 + c_e \theta q^{T^*} = 0, & T < T_2^T \end{cases},$$

where $\hat{y}^{T^*} = q^{T^*} - A - \delta\sqrt{K_t^{T^*}}$, $T_1^T = (t - \theta K_t^{T^*})[F^{-1}(\frac{p - w^T}{p}) + A + \delta\sqrt{K_t^{T^*}}]$ and $T_2^T = (t - \theta K_t^{T^*})[F^{-1}(\frac{p - w^T - c_e(t - \theta K_t^{T^*})}{p}) + A + \delta\sqrt{K_t^{T^*}}]$.

The proof is in the Appendix.

We then compare the strategic interplay between the supplier and the manufacturer when both GCF and TCF are available. The parameters are the same as section 5. In Fig.3, the red lines correspond to the GCF mode and the blue lines to the TCF mode. The solid lines refer to the expected profits of the manufacturer and the dash-lines refer to the profits of the supplier.



(a)LCE condition (b) HCE condition

Fig.7 The profit comparison of the supplier and the manufacturer

We can see that when K_t is a decision variable, the relative profits of the individual player under the two modes are consistent with the results when K_t is an exogenous variable, which indicates that the results in the basic model are robust.

8. Conclusions

This study analyzes a supply chain system consisting of a well-funded supplier and a capital-constrained manufacturer that engage in green investment facing uncertain demand. Different from previous research, we design a GCF model to demonstrate the manufacturer's operational and financing decisions under a hard restriction of carbon emissions. An important prerequisite for obtaining a green loan is that the borrower must make green upgrades and ensure compliance with pre-specified environmental standards. To elaborate on the effectiveness of the GCF, we conduct an in-depth analysis to compare GCF with the traditional TCF, which is subject to a penalty on excessive carbon emissions. The optimal equilibrium solutions under the GCF and TCF mode are obtained and the sensitivities of certain parameters are analyzed. We find that green investment K_t boosts the production quantity, and increases the wholesale price under the HCE condition, but is irrelevant to the wholesale price under the LCE condition. Comparing the carbon emission thresholds under GCF and TCF modes in Proposition 2, we find that compared with the no carbon emission suppression measure, both GCF and TCF can effectively restrain the carbon emissions of the enterprises; and which financing mode has the stronger inhibition effect depends on the bank's interest rate.

Comparing the analytical results about the preferences of the two financing strategies, we find that, given a relatively strict carbon emission policy, the manufacturer can set an appropriate green investment range to achieve a win-win situation with the supplier, while when given a relatively loose carbon emission policy, the choice of manufacturer and supplier is opposite. When comparing the profits with and without carbon emission punishment, an interesting result is that under TCF, the government can set a stringent carbon emission penalty policy to stimulate the firm's green investment, which is also profitable for the companies.

We also compare social welfare under both financing modes with numerical results and find that there are regions in which both the social welfare and profit of the manufacturer can be a win-win. The government can guide manufacturers to make a win-win choice by setting different carbon caps. Comparing social welfare with and without carbon emission constraints, we are surprised to find that the social welfares under the constraint of carbon emissions are lower than that without carbon emissions in some circumstances due to output limitation caused by carbon emission constraint.

This study has the following limitations. In this study, all information is common knowledge to the chain members, but in reality, information asymmetry exists, which could be an interesting direction for further research. In addition, we consider only a carbon emission restriction under GCF and punishment under TCF, whereas further research could be extended to the carbon trade market, in which the firms have the option of selling excess carbon quotas to the market. Another further research direction is to consider the setting that the manufacturer has limited liability and will become bankrupt if the cash flow drops to zero (Chen & Cai, 2011; Kouvelis & Zhao, 2016). We have conducted preliminary research in this direction and found that the limited liability assumption does not affect the qualitative relationship between the individual player's profits under two financing modes. However, it is more challenging to derive equilibrium solutions and analyze the properties of optimal solutions.

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Appendix

Proof of Lemma 1

The end-period cash flow of the manufacturer is

$E\pi_m^G = E[p\min\{D, q^G\}] - (w^G q^G + K_t - K)(1+R)$.

Therefore, the manufacturer's optimization problem can be formulated as

$$\max E\pi_m^G(q^G) = E[p\min\{D, q^G\}] - (w^G q^G + K_t - K)(1+R)$$

$$s.t.\quad (\tau - \theta K_t)q^G \leq T \quad .$$

The first-order and second-order partial derivatives of π_m^G with respect to q^G can be obtained as follows.

$$\frac{dE\pi_m^G}{dq^G} = p[1 - F(q^G - A - \delta\sqrt{K_t})] - w^G(1+R),$$

$$\frac{d^2E\pi_m^G}{dq^{G2}} = -pf(q^G - A - \delta\sqrt{K_t}).$$

We then use the Lagrange multiplier $\lambda \geq 0$ to relax the constraints and solve this problem. The Karush–Kuhn–Tucker condition of the optimization problem can be expressed as

$$\begin{cases} -p[1 - F(q^G - A - \delta\sqrt{K_t})] + w^G(1+R) + \lambda(\tau - \theta K_t) = 0 \\ \lambda[T - (\tau - \theta K_t)q^G] = 0 \\ \lambda \geq 0 \end{cases} .$$

(1) When $\lambda = 0$, $T - (\tau - \theta K_t)q^G \geq 0$,

$$q^{G*} = F^{-1}\left(\frac{p - w^G(1+R)}{p}\right) + A + \delta\sqrt{K_t}.$$

(2) When $\lambda > 0$, $T - (\tau - \theta K_t)q^G = 0$,

$$q^{G*} = \frac{T}{\tau - \theta K_t}.$$

Therefore,

$$q^{G*} = \begin{cases} F^{-1}\left(\frac{p - w^G(1+R)}{p}\right) + A + \delta\sqrt{K_t}, & T \geq T^G \\ \frac{T}{\tau - \theta K_t}, & T < T^G \end{cases},$$

where $T^G = (\tau - \theta K_t)[F^{-1}\left(\frac{p - w^G(1+R)}{p}\right) + A + \delta\sqrt{K_t}]$.

Proof of Lemma 2

When $T \geq T^G$, we have,

$$\frac{d\pi_s^G(w^G)}{dw^G} = \frac{\partial\pi_s^G}{\partial w^G} + \frac{\partial\pi_s^G}{\partial q^G}\frac{\partial q^G}{\partial w^G} = q^{G*} - \frac{(w^G - c)(1+R)}{pf(\hat{y}^G)} = q^{G*} - \frac{1}{h(\hat{y}^G)} \cdot \frac{(w^G - c)(1+R)}{p\bar{F}(\hat{y}^G)},$$

$$\frac{d^2\pi_s^G(w^G)}{dw^{G^2}} = \frac{dq^{G*}}{dw^G} + \left(d\left(-\frac{1}{h(\hat{y}^G)}\right)/dw^G\right) \cdot \frac{(w^G - c)(1+R)}{p\bar{F}(\hat{y}^G)} - \frac{1}{h(\hat{y}^G)} \cdot \left(d\frac{(w^G - c)(1+R)}{p\bar{F}(\hat{y}^G)}/dw^G\right).$$

where $\hat{y}^G = q^{G*} - A - \delta\sqrt{K_t}$ and q^{G*} is the optimal response function with respect to w^G given in Lemma 1, i.e. $q^{G*} = F^{-1}\left(\frac{p - w^G(1+R)}{p}\right) + A + \delta\sqrt{K_t}$.

We will show that all three terms in the above expression of $\frac{d^2 p_s^G(w^G)}{dw^{G^2}}$ are negative. Firstly, from Lemma 1, we have $\frac{dq^{G*}}{dw^G} = -\frac{1+R}{pf(\hat{y}^G)} < 0$. This implies the first term is negative. Together with the definition of $h(\cdot)$, $h(\hat{y}^G)$ is increasing in $\hat{y}^G$, it follows: $d(-\frac{1}{h(\hat{y}^G)})/dw^G = \frac{h'(\hat{y}^G)\cdot\frac{dq^{G*}}{dw^G}}{[h(\hat{y}^G)]^2} < 0$. Note that the wholesale price w^G should not be less than the production cost c, we have, $\frac{(w^G - c)(1+R)}{p\bar{F}(\hat{y}^G)}$ is non-negative. Hence, the second term is negative. Thirdly,

$$d\frac{(w^G - c)(1+R)}{p\bar{F}(\hat{y}^G)}/dw^G = \frac{(1+R)p\bar{F}(\hat{y}^G) + (w^G - c)(1+R)pf(\hat{y})\frac{dq^{G*}}{dw^G}}{[p\bar{F}(\hat{y}^G)]^2}$$

$$= \frac{(1+R)p\bar{F}(\hat{y}^G) + (w^G - c)(1+R)pf(\hat{y})(-\frac{1+R}{pf(\hat{y}^G)})}{[p\bar{F}(\hat{y}^G)]^2} = \frac{(1+R)[p\bar{F}(\hat{y}^G) - w^G(1+R) + c(1+R)]}{[p\bar{F}(\hat{y}^G)]^2} = \frac{c(1+R)^2}{[p\bar{F}(\hat{y}^G)]^2} > 0.$$

Where the last equation is based on the definitions of $\hat{y}^G$ and q^{G*}. It follows that the third term is also negative. Therefore, the second derivate of π_s^G with respect to w^G is less than zero. Solving the first-order condition $\frac{d\pi_s^G(w^G)}{dw^G} = 0$, we have $w^{G*} = \frac{pq^{G*}f(\hat{y}^G)}{1+R} + c$.

When $T < T^G$,
$\frac{dp_s^G}{dw^G} \geq 0$, and therefore, we have the boundary value as the optimal wholesale price: $w^{G*} = \bar{w}$.

Proof of Proposition 1

(1) When $T \geq T^G$,

(i)According to Lemma 1, when $T \geq T^G$, we have q^{G^*} satisfied: $q^{G^*} = F^{-1}(\frac{p - w^G(1+R)}{p}) + A + d\sqrt{K_t}$, we rearrange it into

$$p\bar{F}(q^{G^*} - A - d\sqrt{K_t}) = w^G(1+R), \tag{1}$$

From Lemma 2, we have $w^{G^*} = \frac{pq^{G^*}f(\hat{y}^G)}{1+R} + c$, substituting it into Equation (1), we have

$$p\bar{F}(\hat{y}^G) = pq^{G^*}f(\hat{y}^G) + c(1+R), \tag{2}$$

Divide Equation (2) by $\bar{F}(\hat{y}^G)(1+R)$, we have $\frac{p}{1+R} - \frac{pqh(\hat{y}^G)}{1+R} - \frac{c}{\bar{F}(\hat{y}^G)} = 0$, where $\hat{y}^G = q^{G*} - A - d\sqrt{K_t}$. The first-order partial derivative of q^G with respect to K_t can be obtained as follows.

$$\frac{dq^{G^*}}{dK_t} = \frac{[\frac{pq^{G^*}h'(\hat{y}^G)}{1+R} + \frac{cf(\hat{y}^G)}{\bar{F}(\hat{y}^G)^2}]\frac{d}{2\sqrt{K_t}}}{\frac{ph(\hat{y}^G)}{1+R} + \frac{pq^{G^*}h'(\hat{y}^G)}{1+R} + \frac{cf(\hat{y}^G)}{\bar{F}(\hat{y}^G)^2}} > 0. \tag{3}$$

The above inequality follows from the fact that the demand's cumulative distribution function $F(x)$ is continuous with its probability density function $f(x)>0$, and the failure rate $h(x)=f(x)/\bar{F}(x)$ is increasing in x, where the $\bar{F}(x)$ is defined as $\bar{F}(x)=1-F(x)$.

(ii)From Lemma 2, we have $w^{G^*}(1+R)=pq^{G^*}f(\hat{y}^G)+c(1+R)$, according to the above Equation(2) we can obtain $w^{G^*}(1+R)=p\bar{F}(\hat{y}^G)$. The first-order partial derivative of w^G with respect to K_t can be obtained as follows.

$$\frac{dw^{G^*}}{dK_t}=\frac{-pf(\hat{y}^G)}{1+R}\left[\frac{dq^{G^*}}{dK_t}-\frac{\delta}{2\sqrt{K_t}}\right], \tag{4}$$

From Equation (3), we have $\frac{dq^{G^*}}{dK_t}-\frac{\delta}{2\sqrt{K_t}}=\left[\frac{\frac{pq^{G^*}h'(\hat{y}^G)}{1+R}+\frac{cf(\hat{y}^G)}{\bar{F}(\hat{y}^G)^2}}{\frac{ph(\hat{y}^G)}{1+R}+\frac{pq^{G^*}h'(\hat{y}^G)}{1+R}+\frac{cf(\hat{y}^G)}{\bar{F}(\hat{y}^G)^2}}-1\right]\frac{\delta}{2\sqrt{K_t}}<0$. Thus, we have $\frac{dw^{G^*}}{dK_t}>0$.

(2) When $T<T^G$, $\frac{dq^{G*}}{dK_t}=\frac{\theta T}{(t-\theta K_t)^2}>0$, $w^{G*}=\bar{w}$ is irrelevant to K_t.

Proof of Lemma 3

The end-period cash flow of the manufacturer is
$E[\pi_m^T(q^T)]=E[p\min\{D,q^T\}]-w^Tq^T+K-K_t-c_e[(t-\theta K_t)q^T-T]^+$.

Therefore, the manufacturer's optimization problem can be divided into two situations:

(i) $E[\pi_m^T(q^T)]=E[p\min\{D,q^T\}]-w^Tq^T+K-K_t$

s.t. $(t-\theta K_t)q^T\le T$.

(ii) $E[\pi_m^T(q^T)]=pE[\min\{D,q^T\}]-w^Tq^T+K-K_t-c_e[(t-\theta K_t)q^T-T]$

s.t. $(t-\theta K_t)q^T\ge T$.

We first consider the situation (i).

$E[\pi_m^T(q^T)]=E[p\min\{D,q^T\}]-w^Tq^T+K-K_t$

s.t. $(t-\theta K_t)q^T\le T$.

The first-order and second-order derivatives of $E(\pi_m^T)$ with respect to q^T can be obtained as follows.

$$\frac{dE(\pi_m^T)}{dq^T}=p[1-F(q^T-A-\delta\sqrt{K_t})]-w^T,$$
$$\frac{d^2E(\pi_m^T)}{dq^{T^2}}=-pf(q^T-A-\delta\sqrt{K_t}),$$

We then use the Lagrange multiplier $\lambda \geq 0$ to relax the constraints and solve this problem. The Karush–Kuhn–Tucker condition of the optimization problem can be expressed as

$$\begin{cases} -p[1-F(q^T - A - \delta\sqrt{K_t})] + w^T + \lambda(t-\theta K_t) = 0 \\ \lambda[T-(t-\theta K_t)q^T] = 0 \\ \lambda \geq 0 \end{cases}.$$

(1) When $\lambda = 0$, $T - (t-\theta K_t)q^T \geq 0$,

$$q^{T*} = F^{-1}(\frac{p-w^T}{p}) + A + \delta\sqrt{K_t}.$$

(2) When $\lambda > 0$, $T - (t-\theta K_t)q^T = 0$,

$$q^{T*} = \frac{T}{t-\theta K_t}.$$

Therefore,

$$q^{T*} = \begin{cases} F^{-1}(\frac{p-w^T}{p}) + A + \delta\sqrt{K_t}, & (t-\theta K_t)[F^{-1}(\frac{p-w^T}{p}) + A + \delta\sqrt{K_t}] \leq T \\ \frac{T}{t-\theta K_t}, & (t-\theta K_t)[F^{-1}(\frac{p-w^T}{p}) + A + \delta\sqrt{K_t}] > T \end{cases}.$$

Now consider the situation (ii). The proof process is similar to the situation (i), we have

$$q^{T*} = \begin{cases} F^{-1}(\frac{p-w^T-c_e(t-\theta K_t)}{p}) + A + \delta\sqrt{K_t}, & (t-\theta K_t)[F^{-1}(\frac{p-w^T-c_e(t-\theta K_t)}{p}) + A + \delta\sqrt{K_t}] > T \\ \frac{T}{t-\theta K_t}, & (t-\theta K_t)[F^{-1}(\frac{p-w^T-c_e(t-\theta K_t)}{p}) + A + \delta\sqrt{K_t}] \leq T \end{cases}.$$

To combine the results of two situations, we have

$$q^{T*} = \begin{cases} F^{-1}(\frac{p-w^T}{p}) + A + \delta\sqrt{K_t}, & T > T_1^T \\ \frac{T}{t-\theta K_t}, & T_2^T \leq T \leq T_1^T \\ F^{-1}(\frac{p-w^T-c_e(t-\theta K_t)}{p}) + A + \delta\sqrt{K_t}, & T < T_2^T \end{cases},$$

where $T_1^T = (t-\theta K_t)[F^{-1}(\frac{p-w^T}{p}) + A + \delta\sqrt{K_t}]$ and $T_2^T = (t-\theta K_t)[F^{-1}(\frac{p-w^T-c_e(t-\theta K_t)}{p}) + A + \delta\sqrt{K_t}]$.

Proof of Proposition 2

From Lemma 3, we know that $T_1^T > T_2^T$. We firstly compare T^G and T_1^T. Note that $T^G = (t-\theta K_t)[F^{-1}(\frac{p-w^G(1+R)}{p}) + A + \delta\sqrt{K_t}]$ and $T_1^T = (t-\theta K_t)[F^{-1}(\frac{p-w^T}{p}) + A + \delta\sqrt{K_t}]$. From the proof of Proposition 4 below, we have $q^{G*} < q^{T*}$, which means $F^{-1}(\frac{p-w^G(1+R)}{p}) + A + \delta\sqrt{K_t} < F^{-1}(\frac{p-w^T}{p}) + A + \delta\sqrt{K_t}$. As a result, we have $T^G < T_1^T$.

When compared T^G and T_2^T, where $T^G = (t-\theta K_t)[F^{-1}(\frac{p-w^G(1+R)}{p}) + A + \delta\sqrt{K_t}]$ and $T_2^T = (t-\theta K_t)[F^{-1}(\frac{p-w^T-c_e(t-\theta K_t)}{p}) + A + \delta\sqrt{K_t}]$. Note that the reaction function of q^G is $q^G = F^{-1}(\frac{p-w^G(1+R)}{p}) + A + \delta\sqrt{K_t}$, substituting w^{G*} into it, we have q^{G*} satisfies

$p\bar{F}(\hat{y}^G)[1-q^{G*}h(\hat{y}^G)]=c(1+R)$. Similarly, we have q^{T*} satisfies $p\bar{F}(\hat{y}^T)[1-q^{T*}h(\hat{y}^T)]=c+c_e(t-\theta K_t)$. Define a function $K(q)=\bar{F}(\hat{y})[1-qh(\hat{y})]>0$, where $\hat{y}=q-A-\delta\sqrt{K_t}$ for $q\in[0,\bar{q}]$ where $\bar{q}=\sup\{q \mid qh(\hat{y})\le 1\}$. Note that $qh(\hat{y})$ is non-negative and increasing in $q\ge 0$. Therefore, $\bar{q}$ is well defined. The first derivatives of $K(q)$ with respect to q are given by: $K(q)'=-f(\hat{y})[1-qh(\hat{y})]-\bar{F}(\hat{y})[h(\hat{y})+qh'(\hat{y})]<0$ in the interval $q\in[0,\bar{q}]$, because of $qh(\hat{y})\le 1$ and the properties of $h(\cdot)$ under the assumption of *IGFR*. It follows *K(q)* is decreasing in $q\in[0,\bar{q}]$. We have $K(q^{G*})=\bar{F}(\hat{y}^G)[1-q^{G*}h(\hat{y}^G)]=\frac{c(1+R)}{p}$ and $K(q^{T*})=\bar{F}(\hat{y}^T)[1-q^{T*}h(\hat{y}^T)]=\frac{c+c_e(t-\theta K_t)}{p}$. The above two equations indicate that $q^{G*}h(\hat{y}^G)<1$ and $q^{T*}h(\hat{y}^T)<1$. This implies $q^{G*}<\bar{q}$ and $q^{T*}<\bar{q}$. When $R\le\frac{c_e(t-\theta K_t)}{c}$, we have $K(q^{G*})\le K(q^{T*})$, thus, $q^{G*}\ge q^{T*}$; when $R>\frac{c_e(t-\theta K_t)}{c}$, we have $K(q^{G*})>K(q^{T*})$, thus, $q^{G*}<q^{T*}$. Since $T^G=(t-\theta K_t)q^{G*}$ and $T_2^T=(t-\theta K_t)q^{T*}$, we have $T^G\ge T_2^T$ for $R\le\frac{c_e(t-\theta K_t)}{c}$ and $T^G<T_2^T$ for $R>\frac{c_e(t-\theta K_t)}{c}$.

Proof of Proposition 3

Under GCF, the optimal production quantity without carbon emission constraint is $q^{GB^*}=F^{-1}(\frac{p-w^G(1+R)}{p})+A+\delta\sqrt{K_t}$ and the optimal production quantity with carbon emission constraint is $q^{GL*}=\begin{cases}F^{-1}(\frac{p-w^G(1+R)}{p})+A+\delta\sqrt{K_t}, & T\ge T^G\\ \frac{T}{t-\theta K_t}, & T<T^G\end{cases}$; under HCE condition($T\ge T^G$), $q^{GB*}=q^{GL*}$; Under LCE condition($T<T^G$), $q^{GB*}=F^{-1}(\frac{p-w^G(1+R)}{p})+A+\delta\sqrt{K_t}$, $q^{GL*}=\frac{T}{t-\theta K_t}$, because $T<T^G$, that is $T<(t-\theta K_t)[F^{-1}(\frac{p-w^G(1+R)}{p})+A+\delta\sqrt{K_t}]$, we have $q^{GL*}=\frac{T}{t-\theta K_t}<q^{GB*}=F^{-1}(\frac{p-w^{GB}(1+R)}{p})+A+\delta\sqrt{K_t}$. Therefore we have $q^{GL*}<q^{GB*}$.

Under TCF, the optimal production quantity without carbon emission constraint is $q^{TB*}=F^{-1}(\frac{p-w^T}{p})+A+\delta\sqrt{K_t}$, and the optimal production quantity with carbon emission punishment is $q^{TL*}=\begin{cases}F^{-1}(\frac{p-w^T}{p})+A+\delta\sqrt{K_t}, & T\ge T_1^T\\ \frac{T}{t-\theta K_t}, & T_2^T\le T<T_1^T\\ F^{-1}(\frac{p-w^T-c_e(t-\theta K_t)}{p})+A+\delta\sqrt{K_t}, & T<T_2^T\end{cases}$. Under the HCE condition, we have $q^{TB*}=q^{TL*}$. Under $T_2^T\le T<T_1^T$ the condition, $q^{TL*}=\frac{T}{t-\theta K_t}$, since $T<T_1^T$, which is equal to $T<(t-\theta K_t)[F^{-1}(\frac{p-w^T}{p})+A+\delta\sqrt{K_t}]$, thus, $\frac{T}{t-\theta K_t}<F^{-1}(\frac{p-w^T}{p})+A+\delta\sqrt{K_t}$, we have $q^{TL*}<q^{TB*}$. Under LCE condition, $q^{TL*}=F^{-1}(\frac{p-w^T-c_e(t-\theta K_t)}{p})+A+\delta\sqrt{K_t}$, the optimal equilibrium solution of the supplier's decision is given by $w^{T*}=pq^{T*}f(\hat{y}^T)+c$. Substituting w^{T*} into q^{TB*} and q^{TL*}, we have q^{TB*} satisfies $p\bar{F}(\hat{y}^{TB})[1-q^{TB*}h(\hat{y}^{TB})]=c$, and q^{TL*} satisfies $p\bar{F}(\hat{y}^{TL})[1-q^{TL*}h(\hat{y}^{TL})]=c+c_e(t-\theta K_t)$.

Recalling the function $K(q) = \bar{F}(\hat{y})[1 - qh(\hat{y})]$ defined in the proof of Proposition 2, we have *K(q)* is decreasing in $q \in [0,\bar{q}]$. As mentioned above, we have $K(q^{TB*}) = \bar{F}(\hat{y}^{TB*})[1 - q^{TB*}h(\hat{y}^{TB*})] = \frac{c}{p}$, $K(q^{TL*}) = \bar{F}(\hat{y}^{TL*})[1 - q^{TL*}h(\hat{y}^{TL*})] = \frac{c + c_e(t - \theta K_t)}{p}$. The above two equations indicate that $q^{TB*}h(\hat{y}^{TB*}) < 1$ and $q^{TL*}h(\hat{y}^{TL*}) < 1$. This implies $q^{TB*} < \bar{q}$ and $q^{TL*} < \bar{q}$. thus, $K(q^{TB*}) < K(q^{TL*})$, which yields $q^{TB*} > q^{TL*}$ because *K(q)* is decreasing in $[0,\bar{q}]$. In summary, $q^{TB*} \geq q^{TL*}$.

When refers to the wholesale price, the optimal wholesale price without carbon emission constraint is $w^{GB*} = \frac{pq^{GB*}(w^{GB*}) f(\hat{y}^{GB}(w^{GB*}))}{1+R} + c$. According to Lemma 2, under HCE condition($T \geq T^G$), $w^{GL*} = \frac{pq^{GL*}(w^{GL*}) f(\hat{y}^{GL}(w^{GL*}))}{1+R} + c$, thus, we have $w^{GB*} = w^{GL*}$. While under LCE condition, $w^{GL*} = \bar{w} = p/(1+R)$, thus, $w^{GB*} < w^{GL*}$. In summary, we have $w^{GB*} \leq w^{GL*}$.

When refers to TCF, under HCE condition, apparently $w^{TB*} = w^{TL*}$. Under $T_2^T \leq T < T_1^T$ the condition, $w^{TB*} = pq^{TB*}(w^{TB*}) f(\hat{y}^{TB*}(w^{TB*})) + c = p\bar{F}(\hat{y}^{TB*})$ and $w^{TL*} = p$, thus we have $w^{TB*} < w^{TL*}$. Under LCE condition, the optimal wholesale price $w^{TB*} = pq^{TB*}(w^{TB*}) f(\hat{y}^{TB*}(w^{TB*})) + c = p\bar{F}(\hat{y}^{TB*})$ without carbon emission constraint, which q^{TB*} solves $p\bar{F}(\hat{y}^{TB*}) - pq^{TB*} f(\hat{y}^{TB*}) = c$; the optimal wholesale price $w^{TL*} = pq^{TL*}(w^{TL*}) f(\hat{y}^{TL*}(w^{TL*})) + c = p\bar{F}(\hat{y}^{TL*}) - c_e(t - \theta K_t)$ with carbon emission constraint, which q^{TL*} solves $p\bar{F}(\hat{y}^{TL*}) - pq^{TL*} f(\hat{y}^{TL*}) = c + c_e(t - \theta K_t)$.

Since the wholesale price and the production quantity are corresponding one by one under one financing mode, we compare $w^{TB*} = p\bar{F}(\hat{y}^{TB*})$ and $w^{TL*} = p\bar{F}(\hat{y}^{TL*}) - c_e(t - \theta K_t)$, where q^{TB*} solves $p\bar{F}(\hat{y}^{TB*}) - pq^{TB*} f(\hat{y}^{TB*}) = c$ and q^{TL*} solves $p\bar{F}(\hat{y}^{TL*}) - pq^{TL*} f(\hat{y}^{TL*}) = c + c_e(t - \theta K_t)$. $w^{TB*} - w^{TL*} = p\bar{F}(\hat{y}^{TB*}) - p\bar{F}(\hat{y}^{TL*}) + c_e(t - \theta K_t)$, recalling that $q^{TB*} > q^{TL*}$ and $\bar{F}(\hat{y})$ decreases with q, we have $\bar{F}(\hat{y}^{TB*}) < \bar{F}(\hat{y}^{TL*})$. Therefore, there exists a $\hat{c}_e$, when $c_e > \hat{c}_e$, we have $w^{TB*} > w^{TL*}$; when $c_e \leq \hat{c}_e$, we have $w^{TB*} \leq w^{TL*}$, where $\hat{c}_e = \frac{p\bar{F}(\hat{y}^{TL*}) - p\bar{F}(\hat{y}^{TB*})}{t - \theta K_t}$.

Proof of Proposition 4

	$T < T^G$	$T \geq T^G$	$T \geq T_1^T$
GCF	$q^{G*} = \frac{T}{t - \theta K_t}$ $w^{G*} = \bar{w}$	$q^{G*} = F^{-1}(\frac{p - w^G(1+R)}{p}) + A + \delta\sqrt{K_t}$ $w^{G*} = \frac{pq^{G*} f(\hat{y}^G)}{1+R} + c$	$q^{G*} = F^{-1}(\frac{p - w^G(1+R)}{p}) + A + \delta\sqrt{K_t}$ $w^{G*} = \frac{pq^{G*} f(\hat{y}^G)}{1+R} + c$
	$T < T_2^T$	$T_2^T \leq T < T_1^T$	$T \geq T_1^T$
TCF	$q^{T*} = F^{-1}(\frac{p - w^T - c_e(t - \theta K_t)}{p}) + A + \delta\sqrt{K_t}$ $w^{T*} = pq^{T*} f(\hat{y}^T) + c$	$q^{T*} = \frac{T}{t - \theta K_t}$ $w^{T*} = \bar{w}$	$q^{T*} = F^{-1}(\frac{p - w^T}{p}) + A + \delta\sqrt{K_t}$ $w^{T*} = pq^{T*} f(\hat{y}^T) + c$

(1) When $T \geq T_1^T$

We have the optimal production quantity under GCF: $q^{G*}=F^{-1}(\frac{p-w^G(1+R)}{p})+A+\delta\sqrt{K_t}$, and the wholesale price $w^{G*}=\frac{pq^{G*}f(\hat{y}^G)}{1+R}+c$, where $\hat{y}^G=q^{G*}-A-\delta\sqrt{K_t}$. Substituting w^{G*} into q^{G*}, we have $p\bar{F}(\hat{y}^G)[1-q^{G*}h(\hat{y}^G)]=c(1+R)$.

The optimal production quantity under TCF is $q^{T*}=F^{-1}(\frac{p-w^T}{p})+A+\delta\sqrt{K_t}$, and the wholesale price $w^{T*}=pq^{T*}f(\hat{y}^T)+c$, where $\hat{y}^T=q^{T*}-A-\delta\sqrt{K_t}$. Substituting w^{T*} into q^{T*}, we have $p\bar{F}(\hat{y}^T)[1-q^{T*}h(\hat{y}^T)]=c$.

Recalling the function $K(q)=\bar{F}(\hat{y})[1-qh(\hat{y})]$ defined in the proof of Proposition 2, we have *K(q)* is decreasing in $q\in[0,\bar{q}]$. As mentioned above, we have

$$K(q^{G*})=\bar{F}(\hat{y}^{G*})[1-q^{G*}h(\hat{y}^{G*})]=\frac{c(1+R)}{p},$$

$$K(q^{T*})=\bar{F}(\hat{y}^{T*})[1-q^{T*}h(\hat{y}^{T*})]=\frac{c}{p},$$

Therefore, we have $K(q^{G*})>K(q^{T*})$, which yields $q^{G*}<q^{T*}$ because *K(q)* is decreasing in $[0,\bar{q}]$.

We have the optimal wholesale price under GCF: $w^{G*}=\frac{p\bar{F}(\hat{y}^{G^*})}{1+R}$, which q^{G*} solves $p\bar{F}(\hat{y}^{G*})[1-q^{G*}h(\hat{y}^{G*})]=c(1+R)$. The optimal wholesale price under TCF: $w^{T*}=p\bar{F}(\hat{y}^{T*})$, which q^{T*} solves $p\bar{F}(\hat{y}^{T*})[1-q^{T*}h(\hat{y}^{T*})]=c$. Because $q^{G*}<q^{T*}$, $\bar{F}(\hat{y})$ decreases in q, we have $\bar{F}(\hat{y}^{G^*})>\bar{F}(\hat{y}^{T*})$, thus, there exists a $\hat{R}_1=\frac{\bar{F}(\hat{y}^{G^*})}{\bar{F}(\hat{y}^{T*})}-1$, when $R<\hat{R}_1$, we have $w^{G*}>w^{T*}$, and when $R\geq\hat{R}_1$, we have $w^{G*}\leq w^{T*}$.

(2) When $T<\min\{T^G,T_2^T\}$

We have the optimal production quantity $q^{G*}=\frac{T}{t-\theta K_t}$ under GCF, and $q^{T*}=F^{-1}(\frac{p-w^T-c_e(t-\theta K_t)}{p})+A+\delta\sqrt{K_t}$ under TCF. $T<T_2^T$ is equivalent to $T<(t-\theta K_t)[F^{-1}(\frac{p-w^T-c_e(t-\theta K_t)}{p})+A+\delta\sqrt{K_t}]$, it can be obtained that the minimum value of q^T is $\frac{T}{t-\theta K_t}$, which is q^{G*}, thus, $q^{T*}>q^{G*}$.

We have the optimal wholesale price $w^{G*}=\bar{w}=\frac{p}{1+R}$ under GCF, and $w^{T*}=p\bar{F}(\hat{y}^{T*})-c_e(t-\theta K_t)$ under TCF. There exists a $\hat{R}_2=\frac{p}{p\bar{F}(\hat{y}^{T*})-c_e(t-\theta K_t)}-1$, when $R<\hat{R}_2$, we have $w^{G*}>w^{T*}$; when $R\geq\hat{R}_2$, we have $w^{G*}\leq w^{T*}$.

(3) When $\min\{T^G,T_2^T\}\leq T<T_1^T$

(I) If $T^G\leq T_2^T$ ($R\geq\frac{c_e(t-\theta K_t)}{c}$),

When $T_2^T\leq T<T_1^T$, We have the optimal production quantity under GCF: $q^{G*}=F^{-1}(\frac{p-w^G(1+R)}{p})+A+\delta\sqrt{K_t}$, and the wholesale price $w^{G*}=\frac{pq^{G*}f(\hat{y}^G)}{1+R}+c$, where $\hat{y}^G=q^{G*}-A-\delta\sqrt{K_t}$. The optimal production quantity of TCF is

$q^{T*}=\dfrac{T}{t-\theta K_t}$ and the wholesale price $w^{T*}=\bar{w}=p$. Because $T^G\le T_2^T<T$, we have $q^{G*}<\dfrac{T}{t-\theta K_t}$, thus, $q^{G*}\le q^{T*}$. Comparing the wholesale price, we have $w^{G*}<w^{T*}$.

When $T^G\le T<T_2^T$, We have the optimal production quantity solves $p\bar{F}(\hat{y}^G)[1-q^{G*}h(\hat{y}^G)]=c(1+R)$ under GCF and $p\bar{F}(\hat{y}^{T*})[1-q^{T*}h(\hat{y}^{T*})]=c+c_e(t-\theta K_t)$ under TCF. From the proof of Proposition 2, we know the function $K(q)=\bar{F}(\hat{y})[1-qh(\hat{y})]$ ($\hat{y}=q-A-\delta\sqrt{K_t}$), and $K(q)'=-f(\hat{y})[1-qh(\hat{y})]-\bar{F}(\hat{y})[h(\hat{y})+qh'(\hat{y})]<0$. Because $T^G\le T_2^T$, we have $R\ge\dfrac{c_e(t-\theta K_t)}{c}$, thus, $K(q^{G*})\ge K(q^{T*})$, which yields $q^{G*}\le q^{T*}$. Comparing the wholesale price, we have $w^{G*}=\dfrac{p\bar{F}(\hat{y}^{G^*})}{1+R}$ under GCF and $w^{T*}=p\bar{F}(\hat{y}^{T*})-c_e(t-\theta K_t)$ under TCF, there exists a $\hat{R}_3=\dfrac{p\bar{F}(\hat{y}^{G*})}{p\bar{F}(\hat{y}^{T*})-c_e(t-\theta K_t)}-1$, when $R<\hat{R}_3$, we have $w^{G*}>w^{T*}$, when $R\ge\hat{R}_3$, we have $w^{G*}\le w^{T*}$.

It should be noted that R should be greater than $\dfrac{c_e(t-\theta K_t)}{c}$ under the situation $T^G\le T_2^T$. Let $R_0=\dfrac{c_e(t-\theta K_t)}{c}$, we next prove $\hat{R}_3\ge R_0$, the proof is as follows.

$R_0=\dfrac{c_e(t-\theta K_t)}{c}$ and $\hat{R}_3=\dfrac{p\bar{F}(\hat{y}^{G*})}{p\bar{F}(\hat{y}^{T*})-c_e(t-\theta K_t)}-1$.

$\dfrac{dR_0}{dc_e}=\dfrac{t-\theta K_t}{c}>0$, this implies R_0 is increasing in c_e.

$\dfrac{d\hat{R}_3}{dc_e}=\dfrac{-p\bar{F}(\hat{y}^{G*})[p\bar{F}(\hat{y}^{T*})-c_e(t-\theta K_t)]'}{[p\bar{F}(\hat{y}^{T*})-c_e(t-\theta K_t)]^2}$, where $\hat{y}^{T*}=q^{T*}-A-\delta\sqrt{K_t}$, and q^{T*} solves $p\bar{F}(\hat{y}^{T*})[1-q^{T*}h(\hat{y}^{T*})]=c+c_e(t-\theta K_t)$. The first-order partial derivatives of q^{T*} with respect to c_e can be obtained as follows.

$$\frac{dq^{T*}}{dc_e}=\frac{t-\theta K_t}{-pf(\hat{y}^{T*})[1-q^{T*}h(\hat{y}^{T*})]-p\bar{F}(\hat{y}^{T*})h(\hat{y}^{T*})-pq^{T*}\bar{F}(\hat{y}^{T*})h'(\hat{y}^{T*})},$$ and

$$[p\bar{F}(\hat{y}^{T*})-c_e(t-\theta K_t)]'=-pf(\hat{y}^{T*})\frac{dq^{T*}}{dc_e}-(t-\theta K_t)=$$
$$\frac{(t-\theta K_t)\{pf(\hat{y}^{T*})[1-q^{T*}h(\hat{y}^{T*})]+pq^{T*}\bar{F}(\hat{y}^{T*})h'(\hat{y}^{T*})\}}{-pf(\hat{y}^{T*})[1-q^{T*}h(\hat{y}^{T*})]-p\bar{F}(\hat{y}^{T*})h(\hat{y}^{T*})-pq^{T*}\bar{F}(\hat{y}^{T*})h'(\hat{y}^{T*})}<0.$$

Therefore, $\dfrac{d\hat{R}_3}{dc_e}=\dfrac{-p\bar{F}(\hat{y}^{G*})[p\bar{F}(\hat{y}^{T*})-c_e(t-\theta K_t)]'}{[p\bar{F}(\hat{y}^{T*})-c_e(t-\theta K_t)]^2}>0$.

when $c_e=0$, we have $R_0=0$ and $\hat{R}_3=\dfrac{\bar{F}(\hat{y}^{G*})}{\bar{F}(\hat{y}^{T*})}-1\ge 0$, thus, $R_0\le\hat{R}_3$;

when $c_e=\dfrac{p\bar{F}(\hat{y}^{T*})-c}{t-\theta K_t}$ ($w^{T*}=p\bar{F}(\hat{y}^{T*})-c_e(t-\theta K_t)\ge c$, which indicates $c_e\le\dfrac{p\bar{F}(\hat{y}^{T*})-c}{t-\theta K_t}$). We have $R_0=\dfrac{p\bar{F}(\hat{y}^{T*})-c}{c}$, $\hat{R}_3=\dfrac{p\bar{F}(\hat{y}^{G*})-c}{c}$, thus, $R_0\le\hat{R}_3$.

Recalling that both R_0 and $\hat{R}_3$ are increasing in c_e, therefore, we have $R_0\le\hat{R}_3$.

(II) If $T^G > T_2^T$ $\left(R < \frac{c_e(t-\theta K_t)}{c}\right)$,

When $T^G \le T < T_1^T$, We have the optimal production quantity under GCF: $q^{G*} = F^{-1}\left(\frac{p - w^G(1+R)}{p}\right) + A + \delta\sqrt{K_t}$, and the wholesale price $w^{G*} = \frac{pq^{G*} f(\hat{y}^G)}{1+R} + c$, where $\hat{y}^G = q^{G*} - A - \delta\sqrt{K_t}$. The optimal production quantity of TCF is $q^{T*} = \frac{T}{t-\theta K_t}$, and the wholesale price $w^{T*} = p$. Because $T^G < T$, we have $(t-\theta K_t)[F^{-1}\left(\frac{p - w^G(1+R)}{p}\right) + A + \delta\sqrt{K_t}] < T$, thus, we have $q^{G*} \le q^{T*}$. Comparing the wholesale price, we have $w^{G*} < w^{T*}$.

When $T_2^T \le T < T^G$, We have the optimal production quantity $q^{G*} = q^{T*} = \frac{T}{t-\theta K_t}$, thus, $q^{G*} = q^{T*}$. Comparing the wholesale price, we have $w^{G*} = \frac{p}{1+R}$ and $w^{T*} = p$, thus, $w^{G*} < w^{T*}$.

Proof of Proposition 5

Under the HCE condition ($T \ge T_1^T$),

The supplier's end-period cash flow in the GCF mode is $\pi_s^G = (w^G - c)q^G$, and substituting the optimal wholesale price $w^{G*} = \frac{pq^{G*} f(\hat{y}^G)}{1+R} + c$ into π_s^G, we have $\pi_s^{G*} = \frac{pq^{G*2} f(\hat{y}^{G^*})}{1+R}$.

The supplier's end-period cash flow in the TCF mode is $\pi_s^T = w^T q^T - cq^T$, and substituting the optimal wholesale price $w^{T*} = pq^{T*} f(\hat{y}^T) + c$ into π_s^T, we have $\pi_s^T = pq^{T*2} f(\hat{y}^T)$.

We next prove that π_s^{G*} increases in q^{G*}. $\pi_s^{G*} = \frac{pq^{G*2} f(\hat{y}^{G^*})}{1+R} = \frac{\bar{F}(\hat{y}^{G^*}) pq^{G*2} h(\hat{y}^{G^*})}{1+R}$,

$$\frac{d\pi_s^{G*}}{dq^{G*}} = \frac{-f(\hat{y}^{G^*}) pq^{G*2} h(\hat{y}^{G^*}) + 2\bar{F}(\hat{y}^{G^*}) pq^{G*} h(\hat{y}^{G^*}) + \bar{F}(\hat{y}^{G^*}) pq^{G*2} h'(\hat{y}^{G^*})}{1+R}$$

$$= \frac{pq^{G*} h(\hat{y}^{G^*})[2\bar{F}(\hat{y}^{G^*}) - q^{G*} f(\hat{y}^{G^*})] + \bar{F}(\hat{y}^{G^*}) pq^{G*2} h'(\hat{y}^{G^*})}{1+R}.$$

Recalling that $\bar{F}(\hat{y}^{G^*}) - q^{G*} f(\hat{y}^{G^*}) = \frac{c(1+R)}{p} > 0$, thus, $2\bar{F}(\hat{y}^{G^*}) - q^{G*} f(\hat{y}^{G^*}) > 0$, under the assumption of *IGFR*, we have $\frac{d\pi_s^{G*}}{dq^{G*}} > 0$. In addition, from proposition 4 (1), we know $q^{G*} \le q^{T*}$, $\pi_s^{G*}(q^{G*}) \le \pi_s^{G*}(q^{T*}) = \pi_s^{T*}(q^{T*})$, therefore, we have $\pi_s^{G*}(q^{G*}) \le \pi_s^{T*}(q^{T*})$.

Proof of Lemma 5

Under the bank's GCF, the end-period cash flow of the capital-constrained manufacturer is

$$E\pi_m^G = E[p\min\{D, q^G\}] - (w^G q^G + K_t^G - K)(1+R).$$

Therefore, the manufacturer's optimization problem can be formulated as

$$\max E\pi_m^G(q^G, K_t^G) = E[p\min\{D, q^G\}] - (w^G q^G + K_t^G - K)(1+R)$$

$$s.t.\quad (t - \theta K_t^G)q^G \le T\ .$$

The first-order and second-order partial derivatives of π_m^G with respect to q^G and K_t^G can be obtained as follows.

$$\frac{dE\pi_m^G}{dq^G} = p[1 - F(\hat{y}^G)] - w^G(1+R) \ ,$$

$$\frac{d^2E\pi_m^G}{dq^{G2}} = -pf(\hat{y}^G) \ ,$$

$$\frac{dE\pi_m^G}{dK_t^G} = \frac{\delta p}{2\sqrt{K_t^G}} F(\hat{y}^G) - (1+R) ,$$

$$\frac{d^2E\pi_m^G}{dK_t^{G^2}} = -\frac{\delta pK_t^{G^{-\frac{3}{2}}}}{4} F(\hat{y}^G) - \frac{\delta^2 pK_t^{G^{-1}}}{4} f(\hat{y}^G) \ ,$$

$$\frac{d^2E\pi_m^G}{dq^G dK_t^G} = \frac{\delta pK_t^{G^{-\frac{1}{2}}}}{2} f(\hat{y}^G) . \text{ Where } \hat{y}^G = q^G - A - \delta\sqrt{K_t^G} \ .$$

The Hessian matrix is:

$$H = \begin{bmatrix} -pf(\hat{y}^G) & \frac{\delta pK_t^{G^{-\frac{1}{2}}}}{2} f(\hat{y}^G) \\ \frac{\delta pK_t^{G^{-\frac{1}{2}}}}{2} f(\hat{y}^G) & -\frac{\delta pK_t^{G^{-\frac{3}{2}}}}{4} F(\hat{y}^G) - \frac{\delta^2 pK_t^{G^{-1}}}{4} f(\hat{y}^G) \end{bmatrix} .$$

We have $-pf(\hat{y}^G) < 0$ and $[-pf(\hat{y}^G)][-\frac{\delta pK_t^{G^{-\frac{3}{2}}}}{4} F(\hat{y}^G) - \frac{\delta^2 pK_t^{G}}{4} f(\hat{y}^G)] - [\frac{\delta pK_t^{G^{-\frac{1}{2}}}}{2} f(\hat{y}^G)]^2 = \frac{\delta p^2 K_t^{G^{-\frac{3}{2}}}}{4} f(\hat{y}^G) F(\hat{y}^G) > 0$. Thus we can see the Hessian matrix is negative definite and $E\pi_m^G$ is jointly concave with respect to q^G and K_t^G .

We then use the Lagrange multiplier $\lambda \geq 0$ to relax the constraints and solve this problem. The Karush–Kuhn–Tucker condition of the optimization problem can be expressed as

$$\begin{cases} -p[1-F(\hat{y}^G)] + w^G(1+R) + \lambda(\tau - \theta K_t^G) = 0 \\ -\frac{\delta p}{2\sqrt{K_t^G}} F(\hat{y}^G) + (1+R) - \lambda\theta q^G = 0 \\ \lambda[T - (\tau - \theta K_t^G)q^G] = 0 \\ \lambda \geq 0 \end{cases} ,$$

(1) When $\lambda = 0$, $T - (\tau - \theta K_t^G)q^G \geq 0$,

$q^{G*} = F^{-1}(\frac{p - w^G(1+R)}{p}) + A + \delta\sqrt{K_t^G}$, K_t^{G*} satisfies $\frac{\delta p}{2\sqrt{K_t^{G^*}}} F(\hat{y}^{G^*}) - (1+R) = 0$.

(2) When $\lambda > 0$, $T - (\tau - \theta K_t^G)q^G = 0$,

$q^{G*} = \frac{T}{\tau - \theta K_t^G}$, K_t^{G*} satisfies

$\theta q^{G^*}\{p[1 - F(\hat{y}^{G^*})] - w^G(1+R)\} - (\tau - \theta K_t^{G*})[-\frac{\delta p}{2\sqrt{K_t^{G*}}} F(\hat{y}^{G^*}) + (1+R)] = 0$ and $\lambda = \frac{p[1 - F(\hat{y}^G)] - w^G(1+R)}{\tau - \theta K_t^{G*}}$.

Therefore,

$$q^{G*}=\begin{cases} F^{-1}(\frac{p-w^G(1+R)}{p})+A+\delta\sqrt{K_t^{G^*}}, & T\geq T^G \\ \frac{T}{\tau-\theta K_t^{G^*}}, & T<T^G \end{cases}$$, and $K_t^{G^*}$ satisfies

$$\begin{cases} \frac{\delta p}{2\sqrt{K_t^{G^*}}}F(\hat{y}^{G^*})-(1+R)=0, & T\geq T^G \\ \theta q^{G^*}[p\bar{F}(\hat{y}^{G^*})-w^G(1+R)]-(\tau-\theta K_t^G)[-\frac{\delta p}{2\sqrt{K_t^G}}F(\hat{y}^{G^*})+(1+R)]=0, & T<T^G \end{cases},$$

where $T^G=(\tau-\theta K_t^{G^*})[F^{-1}(\frac{p-w^G(1+R)}{p})+A+\delta\sqrt{K_t^{G^*}}]$, $\hat{y}^{G^*}=q^{G^*}-A-\delta\sqrt{K_t^{G^*}}$.

Now consider TCF. The end-period cash flow of the manufacturer is
$E[\pi_m^T(q^T,K_t^T)]=E[p\min\{D,q^T\}]-w^Tq^T+K-K_t^T-c_e[(\tau-\theta K_t^T)q^T-T]^+$.

Therefore, the manufacturer's optimization problem can be divided into two situations:

(i) $E[\pi_m^T(q^T,K_t^T)]=E[p\min\{D,q^T\}]-w^Tq^T+K-K_t^T$

$s.t.\ (\tau-\theta K_t^T)q^T\leq T$

(ii) $E[\pi_m^T(q^T,K_t^T)]=E[p\min\{D,q^T\}]-w^Tq^T+K-K_t^T-c_e[(\tau-\theta K_t^T)q^T-T]$

$s.t.\ (\tau-\theta K_t^T)q^T\geq T$

We first consider the situation (i).

$E[\pi_m^T(q^T,K_t^T)]=E[p\min\{D,q^T\}]-w^Tq^T+K-K_t^T$

$s.t.\ (\tau-\theta K_t^T)q^T\leq T$

The proof process is similar to that of GCF. The optimal reaction functions of production quantity and green investment are

$$q^{T*}=\begin{cases} F^{-1}(\frac{p-w^T}{p})+A+\delta\sqrt{K_t^{T^*}}, & T\geq T_1^T \\ \frac{T}{\tau-\theta K_t^{T^*}}, & T<T_1^T \end{cases}$$, and $K_t^{T^*}$ satisfies

$$\begin{cases} \frac{\delta p}{2\sqrt{K_t^{T^*}}}F(\hat{y}^{T^*})-1=0, & T\geq T_1^T \\ \theta q^{T^*}\{p[1-F(\hat{y}^{T^*})]-w^T\}-(\tau-\theta K_t^{T^*})[1-\frac{\delta p}{2\sqrt{K_t^{T^*}}}F(\hat{y}^{T^*})]=0, & T<T_1^T \end{cases},$$

Where $T_1^T=(\tau-\theta K_t^{T^*})[F^{-1}(\frac{p-w^T}{p})+A+\delta\sqrt{K_t^{T^*}}]$, $\hat{y}^{T^*}=q^{T^*}-A-\delta\sqrt{K_t^{T^*}}$.

Now consider the situation (ii).

The expected end-period cash flow of the manufacturer is given as follows:

(2) $E[\pi_m^T(q^T,K_t^T)] = E[p\min\{D,q^T\}] - w^T q^T + K - K_t^T - c_e[(t-\theta K_t^T)q^T - T]$

s.t. $(t-\theta K_t^T)q^T \geq T$.

The first-order and second-order partial derivatives of π_m^T with respect to q^T and K_t^T can be obtained as follows.

$$\frac{dE\pi_m^T}{dq^T} = p[1-F(\hat{y}^T)] - w^T - c_e(t-\theta K_t^T) \ ,$$

$$\frac{d^2E\pi_m^T}{dq^{T^2}} = -pf(\hat{y}^T),$$

$$\frac{dE\pi_m^T}{dK_t^T} = \frac{\delta p}{2\sqrt{K_t^T}}F(\hat{y}^T) - 1 + c_e\theta q^T,$$

$$\frac{d^2E\pi_m^T}{dK_t^{T^2}} = -\frac{\delta p K_t^{T^{-\frac{3}{2}}}}{4}F(\hat{y}^T) - \frac{\delta^2 p K_t^{T^{-1}}}{4}f(\hat{y}^T),$$

$$\frac{d^2E\pi_m^T}{dq^T dK_t^T} = \frac{\delta p K_t^{T^{-\frac{1}{2}}}}{2}f(\hat{y}^T) + c_e\theta.$$

The Hessian matrix is:

$$H = \begin{bmatrix} -pf(\hat{y}^T) & \frac{\delta p K_t^{T^{-\frac{1}{2}}}}{2}f(\hat{y}^T) + c_e\theta \\ \frac{\delta p K_t^{T^{-\frac{1}{2}}}}{2}f(\hat{y}^T) + c_e\theta & -\frac{\delta p K_t^{T^{-\frac{3}{2}}}}{4}F(\hat{y}^T) - \frac{\delta^2 p K_t^{T^{-1}}}{4}f(\hat{y}^T) \end{bmatrix}.$$

Only when $H = \delta p K_t^{T^{-\frac{1}{2}}} f(\hat{y}^T)[\frac{\pi}{4}K_t^{T^{-1}}F(\hat{y}^T) - c_e\theta] - c_e^2\theta^2 > 0$, we have

$q^{T*} = F^{-1}(\frac{p - w^T - c_e(t-\theta K_t^{T^*})}{p}) + A + \delta\sqrt{K_t^{T^*}}$, and $K_t^{T^*}$ satisfies $\frac{\delta p}{2\sqrt{K_t^{T^*}}}F(\hat{y}^{T^*}) - 1 + c_e\theta q^{T^*} = 0$.

Therefore, the manufacturer's optimal decisions are as follows:

$$q^{T*} = \begin{cases} F^{-1}(\frac{p - w^T - c_e(t-\theta K_t^{T^*})}{p}) + A + \delta\sqrt{K_t^{T^*}}, & T < T_2^T \\ \frac{T}{t-\theta K_t^{T^*}}, & T \geq T_2^T \end{cases}$$

, and $K_t^{T^*}$ satisfies

$$\begin{cases} \frac{\delta p}{2\sqrt{K_t^{T^*}}}F(\hat{y}^{T^*}) - 1 + c_e\theta q^{T^*} = 0, & T < T_2^T \\ \theta q^{T^*}[p\bar{F}(\hat{y}^{T^*}) - w^T] - (t-\theta K_t^{T^*})[1 - \frac{\delta p}{2\sqrt{K_t^G}}F(\hat{y}^{T^*})] = 0, & T \geq T_2^T \end{cases},$$

where $T_2^T = (t-\theta K_t^{T^*})[F^{-1}(\frac{p - w^T - c_e(t-\theta K_t^{T^*})}{p}) + A + \delta\sqrt{K_t^{T^*}}]$.

To combine the results of two situations, we have

$$q^{T^*} = \begin{cases} F^{-1}\left(\dfrac{p - w^T}{p}\right) + A + \delta\sqrt{K_t^{T^*}}, & T > T_1^T \\ \dfrac{T}{t - \theta K_t^{T^*}}, & T_2^T \le T \le T_1^T \\ F^{-1}\left(\dfrac{p - w^T - c_e(t - \theta K_t^{T^*})}{p}\right) + A + \delta\sqrt{K_t^{T^*}}, & T < T_2^T \end{cases}$$, and $K_t^{T^*}$ satisfies

$$\begin{cases} \dfrac{\delta p}{2\sqrt{K_t^{T^*}}} F(\hat{y}^{T^*}) - 1 = 0, & T \ge T_1^T \\ \theta q^{T^*}[p\bar{F}(\hat{y}^{T^*}) - w^T] - (t - \theta K_t^{T^*})[1 - \dfrac{\delta p}{2\sqrt{K_t^{T}}} F(\hat{y}^{T^*})] = 0, & T_2^T \le T < T_1^T \\ \dfrac{\delta p}{2\sqrt{K_t^{T^*}}} F(\hat{y}^{T^*}) - 1 + c_e \theta q^{T^*} = 0, & T < T_2^T \end{cases},$$

where $\hat{y}^{T^*} = q^{T^*} - A - \delta\sqrt{K_t^{T^*}}$, $T_1^T = (t - \theta K_t^{T^*})[F^{-1}(\dfrac{p - w^T}{p}) + A + \delta\sqrt{K_t^{T^*}}]$ and $T_2^T = (t - \theta K_t^{T^*})[F^{-1}(\dfrac{p - w^T - c_e(t - \theta K_t^{T^*})}{p}) + A + \delta\sqrt{K_t^{T^*}}]$.