



Research article

Green subsidy strategies in capital-constrained supply chains with manufacturer fairness concerns

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Abstract: Capital constraints remain a major barrier to green transformation in supply chains, particularly for upstream manufacturers that must finance costly green investment. Yet little is known about how a manufacturer's fairness concern interacts with capital constraints to shape the effectiveness of retailer-led green subsidy strategies. To address this gap, we developd a Stackelberg game between a capital-constrained manufacturer and a financially strong retailer, and compared three retailer-led financing strategies: the production loan (strategy PL), the green loan (strategy GL), and the cost-sharing loan (strategy CL). We derived equilibrium decisions under each strategy, identified the parameter regions in which each strategy is preferred, and further examined how fairness concern alters their comparative performance. The results showed that Strategy PL can relieve short-term liquidity pressure but cannot provide sustained incentives for green investment. Strategy GL is most effective when green investment is relatively inefficient, whereas Strategy CL becomes superior when green investment efficiency is sufficiently high and the retailer's cost participation can materially reduce the manufacturer's burden. Moreover, the manufacturer's fairness concern significantly moderates green investment incentives, profit allocation, and strategy ranking, and may even reverse the relative attractiveness of Strategy GL and Strategy CL. These findings offer new insights into the joint design of financing and coordination mechanisms for sustainable supply chains.

Keywords: green subsidy; capital constraints; retailer-led; cost-sharing; fairness concern

Mathematics Subject Classification: 91A35, 91A80

1. Introduction

The escalating global environmental crisis has established sustainable development as a core priority in the global governance agenda. At the national policy level, initiatives such as China's "dual-carbon" targets are driving the systemic transition of the economy toward a green and low-carbon model [1]. At the market level, growing consumer environmental awareness and increasing preference for green products have become key drivers for corporate green transformation [2]. Empirical evidence shows that these changes are reshaping market competition, and firms are increasingly seeking to improve their competitiveness through green supply chain management (GSCM). Against this backdrop, GSCM has become a key approach for firms to balance environmental performance and economic benefits [3,4].

Despite these strong drivers for green development, the widespread adoption of green practices in supply chains is largely constrained by financing shortages. Green R&D and low-carbon equipment upgrades require large upfront capital investment, and the persistent funding gaps among small- and medium-sized manufacturers have become a major bottleneck for the green transition of entire supply chains [5]. While supply chain finance (SCF) is widely recognized as an effective tool to ease upstream financing difficulties [6], traditional SCF programs are mainly designed to support routine production activities. When manufacturers have to bear the full cost and financing risks of additional, higher-risk green investments, their willingness to carry out green initiatives decreases significantly, which often leads to the delay or cancellation of planned green projects [7,8].

Existing research on green supply chain coordination has identified cost-sharing as an effective contractual mechanism to incentivize manufacturers to improve the environmental performance of products [9], but most of these studies have critical limitations in their core assumptions. The majority of this literature assumes that supply chain members have sufficient financial resources, ignoring a common practical problem: under strict capital constraints, manufacturers may be unable to fulfill even the agreed cost-sharing obligations, which directly undermines the feasibility and effectiveness of traditional coordination contracts [10]. This observation points to a key but under-explored point in existing research: financing functions and coordination mechanisms are closely coupled in practice. Providing production credit alone cannot fully solve the double-marginalization problem that weakens incentives for green investment, while traditional cost-sharing contracts become unenforceable when manufacturers face severe capital constraints.

In practice, leading retailers are increasingly stepping into the role of financiers to bridge this gap, offering various subsidy-driven incentives to their upstream partners. Common retailer-led strategies include providing loans exclusively for production activities, offering dedicated credit for green investment projects, and signing cost-sharing agreements for manufacturers' environmental upgrades [11]. For example, Starbucks pays a premium for sustainably sourced coffee beans, and Walmart has launched cost-sharing programs with its suppliers for packaging reduction initiatives. However, existing research has not conducted a systematic comparison of these distinct retailer-led green subsidy modes (production loans, green investment loans, and hybrid cost-sharing loans) within a unified analytical framework that explicitly considers the manufacturer's binding capital constraint [12]. The comparative impacts of these strategies on product greenness, profit distribution, and supply chain resilience to financing cost fluctuations remain unclear, which creates a critical decision-making gap for supply chain practitioners.

Beyond financial and operational factors, the manufacturer's fairness concern is also a key factor affecting the effectiveness of retailer-led green subsidy schemes, and this behavioral dimension has not been fully explored in relevant existing research. A large body of research in behavioral operations management has confirmed that firms are not only motivated by profit maximization, but also by fairness preferences. Fairness concern, defined as a firm's aversion to inequitable profit outcomes, can significantly affect operational decisions in decentralized supply chains. When a manufacturer makes costly green investments while relying on the retailer for financing, it becomes highly sensitive to the distribution of profits between supply chain partners [13, 14]. This behavioral factor can distort green investment and pricing decisions, and even threaten the stability of the cooperative relationship, as shown in real-world cases where suppliers ended partnerships over perceived unfairness [15]. While recent studies have started to examine fairness concerns in green supply chains, most of them focus on contexts with government subsidies or consumer environmental awareness [16]. The specific role of the manufacturer's fairness concern in retailer-led green subsidy schemes under capital constraints remains a significant research gap.

To fill these gaps, this paper develops a Stackelberg game model consisting of a capital-constrained manufacturer and a well-capitalized retailer, with the retailer acting as the leader. We compare three retailer-led green subsidy strategies: Strategy PL, Strategy GL, and Strategy CL. The model first characterizes the equilibrium outcomes under each strategy and then extends the analysis by introducing the manufacturer's fairness concern to investigate how behavioral preferences reshape the effectiveness of financing and coordination. This setting enables us to address three research questions:

- (1) How do the three retailer-led strategies differ in their effects on green investment, pricing, and profit allocation?
- (2) Under what conditions does each strategy dominate from the perspectives of the retailer, the manufacturer, and the supply chain as a whole?
- (3) How does the manufacturer's fairness concern alter the relative attractiveness of these strategies?

This study makes three contributions. First, it integrates supply chain finance and green coordination in a unified game-theoretic framework that explicitly accounts for binding capital constraints, thereby extending the GSCM literature beyond frictionless financing assumptions. Second, it provides a systematic comparison of three practically relevant retailer-led financing strategies and derives clear boundary conditions under which each strategy performs best, offering actionable implications for retail managers and supply chain designers. Third, by incorporating the manufacturer's fairness concern, it enriches the behavioral operations literature and shows that fairness preferences can substantially change the incentive effects and comparative performance of alternative green financing mechanisms. Taken together, our results offer theoretical and managerial insights for designing green financing arrangements that are not only economically effective but also behaviorally robust.

2. Literature review

This section reviews three interrelated streams of literature: green supply chain management (GSCM), green supply chain finance (GSCF), and fairness concerns. While prior studies provide important insights into sustainability transitions, financing mechanisms, and behavioral factors, an integrated framework that simultaneously incorporates capital constraints, retailer-led financing, and fairness concerns remains underdeveloped.

2.1. Theoretical evolution of GSCM

GSCM has evolved from a compliance-oriented practice into a strategic imperative driven by increasing regulatory pressure and market demand [2,4]. Policy initiatives, such as China's "dual carbon" targets, alongside growing consumer preference for environmentally friendly products, have compelled firms to embed sustainability into their core operational strategies. Empirical evidence suggests that successful GSCM implementation relies heavily on internal capabilities, including managerial commitment, corporate social responsibility (CSR) engagement, and innovation capacity [17].

From an operational perspective, GSCM enhances firm performance primarily through green innovation in products, processes, and managerial practices. However, such transformation typically requires substantial upfront investment in R&D and organizational restructuring [3, 4]. Although external enablers—such as government subsidies and digital technologies—can reduce transaction costs and improve supply chain transparency [18], capital availability remains a critical constraint, particularly for small- and medium-sized manufacturers [5].

Overall, the literature converges on the view that financial constraints constitute a key barrier to green transformation. However, existing studies predominantly focus on capability development and external drivers, with limited attention to how financially constrained firms sustain long-term green investment. This gap motivates the integration of financing mechanisms into the GSCM framework.

2.2. Innovations in green supply chain finance

GSCF extends traditional supply chain finance by embedding environmental objectives into financing decisions. Instruments such as sustainability-linked loans and green credit have been widely recognized for their role in alleviating liquidity constraints and promoting environmentally responsible investment [11, 19]. These mechanisms are particularly effective in financially constrained environments [20].

More recently, an emerging stream of research highlights the increasing role of dominant downstream firms—especially retailers—in directly financing upstream manufacturers through loans, subsidies, or cost-sharing arrangements [11, 20]. This development shifts green financing from an external capital acquisition problem to an internal supply chain coordination issue.

Despite these advances, most existing models implicitly assume sufficient capital availability and do not explicitly consider binding financial constraints. Under such constraints, traditional coordination contracts may become infeasible or suboptimal [10]. Consequently, the literature has yet to systematically examine how different financing mechanisms perform when capital is limited, nor how financing and operational decisions should be jointly optimized.

2.3. Fairness concerns in GSCM

Fairness concerns have been widely recognized as an important behavioral factor in supply chain management. Firms often evaluate outcomes relative to their partners, and such preferences can significantly influence pricing, investment, and coordination decisions [21, 22]. These effects are particularly salient in asymmetric supply chains, where weaker firms face both dependency and financial pressure [8, 23].

In the context of green supply chains, fairness concerns have been shown to affect investment incentives, product greenness, and coordination efficiency [8, 23]. Prior studies further examine their interaction with policy instruments and market factors, demonstrating that subsidies and consumer

preferences may either mitigate or amplify fairness-driven distortions [24,25].

Despite these advances, the existing literature largely abstracts from financing structures, particularly retailer-led financing under capital constraints. When a retailer acts simultaneously as channel leader and financial provider, fairness concerns may influence not only investment incentives but also the relative performance of alternative financing mechanisms. This interaction remains largely unexplored.

Collectively, prior studies suggest that (i) GSCM is fundamentally constrained by financial resources, (ii) GSCF provides mechanisms to alleviate such constraints, and (iii) fairness concerns shape supply chain coordination outcomes. However, these three streams have largely evolved in isolation. In particular, the joint role of capital constraints, retailer-led financing, and fairness concerns has not been systematically examined within a unified framework.

Table 1. Literature positioning and comparison.

Study	Capital constraint	Green	Fairness concern	Coordination mechanism
[2]	–	✓	–	Hybrid cost-sharing and revenue-sharing contract
[8]	–	✓	D	Wholesale price contract
[9]	–	✓	–	Cost-sharing contract
[13]	–	✓	R	Profit-sharing mechanisms
[22]	–	–	M	Wholesale pricing with fairness
[23]	–	✓	M	Profit-sharing contract
[24]	–	✓	–	Government subsidy design under information asymmetry
[26]	–	✓	M	Cost-sharing joint commission contract
[10]	✓	–	–	Revenue-sharing contracts with working capital coordination
[19]	✓	–	–	Supply chain financing vs. supplier-guaranteed financing
[27]	✓	–	–	Pay-back and cost-sharing contracts
[28]	✓	✓	–	Government subsidy modes
[29]	✓	✓	–	Bank financing vs. manufacturer financing
[30]	✓	✓	R	Manufacturer finance vs. manufacturer investment
This study	✓	✓	M	Production loan, green loan, and cost-sharing loan strategies

Note: M = Manufacturer fairness concern; R = Retailer fairness concern; D = Dual fairness concerns.

To position our study within the existing literature, Table 1 provides a structured comparison of representative works across these dimensions, highlighting their key assumptions and limitations. The comparison reveals a clear gap in integrating financial constraints, endogenous financing strategies, and behavioral preferences.

2.4. Research contributions

To address the above gap, this paper develops a Stackelberg game between a capital-constrained manufacturer and a well-funded retailer. We consider three retailer-led financing strategies, namely, the production loan (PL) strategy, the green loan (GL) strategy, and the cost-sharing loan (CL) strategy, and incorporate fairness concerns to capture behavioral preferences.

This study contributes to the literature in three main aspects. First, it extends the GSCM literature by explicitly incorporating capital constraints into the analysis of green investment decisions, which are typically examined without financing frictions. Second, it contributes to GSCF research by comparing multiple retailer-led financing mechanisms within a unified analytical framework, whereas most existing studies focus on a single financing scheme. Third, it enriches the behavioral operations literature by introducing fairness concerns into a financially constrained setting and examining their impact on equilibrium outcomes, a dimension that has received limited attention in prior work.

Our analysis characterizes the conditions under which each financing mechanism dominates, thereby providing boundary-based insights for the design of green financing contracts in decentralized supply chains.

3. Problem description and model formulation

This study constructs a two-echelon green supply chain comprising a capital-constrained manufacturer and a retailer, where the retailer acts as the Stackelberg leader by providing operational financing. Upon receiving funds, the manufacturer, as the follower, undertakes product manufacturing and makes green technology investments. Consistent with the modeling approach in prior literature [31], the retail price p is defined as the sum of the manufacturer's wholesale price w and the retailer's unit profit margin y , i.e., $p = w + y$. Based on the financing scope and cost-sharing mechanisms, we develop and analyze three distinct strategies, as schematically illustrated in Figure 1:

- **Production Loan (Strategy PL):** The manufacturer borrows funds only to cover the basic production cost, with no allocation for green investment (hence, the green level $e = 0$). The demand function in this strategy depends solely on the selling price.
- **Green Loan (Strategy GL):** The manufacturer borrows for the basic production cost and independently finances the green technology investment. The associated R&D cost is $\frac{1}{2}ke^2$. Consequently, the market demand function incorporates a positive dependence on the product's green level e .
- **Cost-sharing Loans (Strategy CL):** This strategy extends Strategy GL by introducing a coordination mechanism: the retailer shares a proportion t of the green technology investment cost, thereby alleviating the manufacturer's dual financial burden.

We conduct a quantitative analysis of the equilibrium outcomes, including financing scale, optimal green level, and profit distribution, under these three strategies. The objective is to delineate the specific conditions under which the performance of individual supply chain members and the overall system can be simultaneously optimized.

The key variables and parameters employed in our strategies are summarized in Table 2. To establish the theoretical foundation, the following assumptions are stipulated:

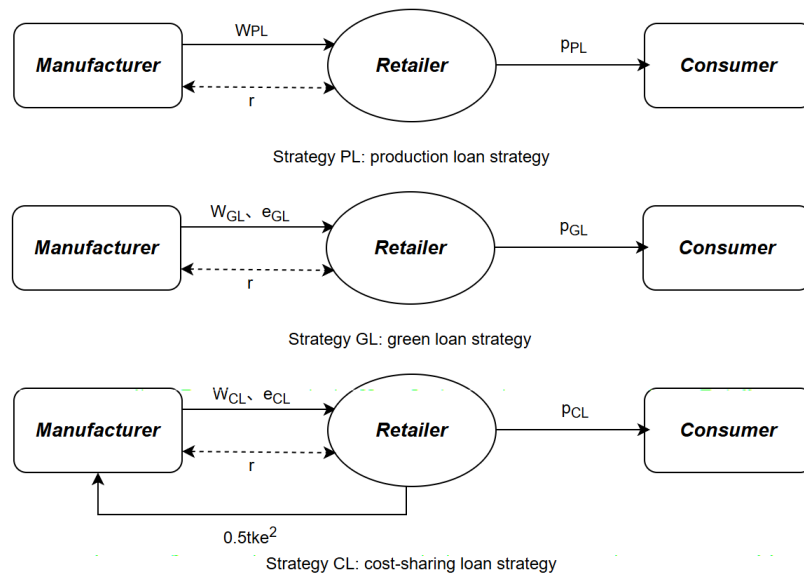


Figure 1. Schematic diagram of the three operational strategies.

Table 2. Model variables and parameters.

Notation	Description
c	Unit production cost of the manufacturer ($0 < c < 1$)
k	Green investment cost coefficient
t	Proportion of green cost shared by the retailer ($0 < t < 1$)
e_i	Green level under Strategy i
p_i	Retail price under Strategy i
w_i	Wholesale price under Strategy i
y	Retailer's unit profit margin
r	Interest rate ($0 < r < 1$)
D_i	Consumer demand under Strategy i
π_M^i	Manufacturer's profit under Strategy i
π_R^i	Retailer's profit under Strategy i

- (1) **Decision Sequence:** The model follows a Stackelberg game. The retailer, as the leader, first determines its unit profit margin y and, under Strategy CL, the cost-sharing ratio t . The manufacturer, as the follower, subsequently chooses the product's green level e and the wholesale price w .
- (2) **Decision-Maker Rationality:** The retailer and the manufacturer are fully rational, risk-neutral decision-makers, each aiming to maximize its own profit. Risk aversion and additional risk premiums are not considered.
- (3) **Information Structure:** Information is symmetric among the manufacturer, the retailer, and consumers. All decisions and parameters are common knowledge.
- (4) **Demand Function:** Consumer demand depends on both the retail price p and the product's green level e , decreasing in price and increasing in greenness [32]. Following the standard linear specification in the literature [31], we define $D(p, e) = 1 - p + e$, where $e = 0$ under Strategy PL, whereas $e > 0$ under Strategies GL and CL.
- (5) **Cost Structure:** The manufacturer incurs a unit production cost c . In addition, green investment generates a convex cost in the green level [33, 34], given by $C_g(e) = \frac{1}{2}ke^2$, where $k > 0$ is the green investment cost coefficient. Under Strategy GL, this cost is fully borne by the manufacturer. Under Strategy CL, the retailer shares a fraction t of the green investment cost, while the manufacturer bears the remaining fraction $1 - t$.

Based on the above assumptions, we next formulate the profit functions under Strategy PL, Strategy GL, and Strategy CL. We then derive the corresponding Stackelberg equilibria and compare the three strategies in terms of product greenness, pricing decisions, and profit allocation.

4. Without fairness concern

4.1. Equilibrium analysis

4.1.1. Strategy PL

Strategy PL serves as the baseline case. The capital-constrained manufacturer borrows only to cover basic production costs, and no green investment is undertaken, i.e., $e_{PL} = 0$. The retailer, as the Stackelberg leader, first sets its unit profit margin y , while the manufacturer then determines the wholesale price w to maximize profit. Under the linear demand specification, the retail demand is $D_{PL} = 1 - p_{PL}$, $p_{PL} = w_{PL} + y_{PL}$. The corresponding profit functions are

$$\pi_M^{PL} = (w_{PL} - c)D_{PL} - crD_{PL}, \quad (4.1)$$

$$\pi_R^{PL} = (p_{PL} - w_{PL})D_{PL} + crD_{PL}. \quad (4.2)$$

Lemma 1. *Under Strategy PL, the equilibrium wholesale price, retailer's unit profit margin, and equilibrium retail price are, respectively: $w_{PL} = \frac{3c+4cr+1}{4}$, $y_{PL} = \frac{1-2cr-c}{2}$, $p_{PL} = \frac{3+c}{4}$.*

Building upon Lemma 1, the optimal demand, manufacturer's profit, and retailer's profit under Strategy PL can be further derived as: $D_{PL} = \frac{1-c}{4}$, $\pi_m^{PL} = \frac{(1-c)^2}{16}$, $\pi_r^{PL} = \frac{3(1-c)^2}{16}$.

4.1.2. Strategy GL

Strategy GL extends PL by allowing the manufacturer to invest endogenously in green technology. The retailer still sets the unit margin y first, and the manufacturer then chooses both the wholesale price w and the green level e . Demand depends on both price and greenness: $D_{GL} = 1 - p_{GL} + e_{GL}$, $p_{GL} = w_{GL} + y_{GL}$. The profit functions are

$$\pi_M^{GL} = (w_{GL} - c)D_{GL} - \frac{1}{2}ke_{GL}^2 - \left(cD_{GL} + \frac{1}{2}ke_{GL}^2\right)r, \quad (4.3)$$

$$\pi_R^{GL} = (p_{GL} - w_{GL})D_{GL} + \left(cD_{GL} + \frac{1}{2}ke_{GL}^2\right)r. \quad (4.4)$$

Lemma 2. Under Strategy GL, the equilibrium product green level and wholesale price are derived as $e_{GL}^* = \frac{(1-c)(r+1)}{4k(r+1)^2-3(r+1)+1}$ and $w_{GL}^* = \frac{4ck(r+1)^3+(3c-k+ck)(r+1)^2+c(r+1)}{4k(r+1)^2-3(r+1)+1}$, respectively. Correspondingly, the retailer's per-unit profit margin and the equilibrium retail price are given by $y_{GL}^* = \frac{(r+1)^2(3c+2k+2ck)-(2c+2)(r+1)-4ck(r+1)^3+1}{4k(r+1)^2-3(r+1)+1}$ and $p_{GL}^* = \frac{(3k+ck)(r+1)^2-(c+2)(r+1)+1}{4k(r+1)^2-3(r+1)+1}$, respectively.

The corresponding retailer margin follows directly from $y_{GL}^* = p_{GL}^* - w_{GL}^*$, and the equilibrium demand and profits are $D_{GL}^* = -\frac{k(c-1)(r+1)^2}{4k(r+1)^2-3(r+1)+1}$, $\pi_R^{GL} = \frac{k(c-1)^2(r+1)^2}{2[4k(r+1)^2-3(r+1)+1]}$, $\pi_M^{GL} = \frac{k(c-1)^2(r+1)^3(2k(r+1)-1)}{2[4k(r+1)^2-3(r+1)+1]^2}$. The above equilibrium solutions are valid and feasible only if the technological parameter satisfies the critical threshold condition $k > \hat{k}_1 = \frac{1}{2(1+r)}$.

Corollary 1. Based on Lemma 2, Table 3 summarizes how the key decision variables change with the green investment cost coefficient k and financing rate r under Strategy GL. The manufacturer's profit is non-monotone in k : $\partial\pi_m^{GL}/\partial k > 0$ for $\hat{k}_1 < k < \hat{k}_3$ and $\partial\pi_m^{GL}/\partial k < 0$ for $k > \hat{k}_3$, where $\hat{k}_1 = \frac{1}{2(1+r)}$ and $\hat{k}_3 = \frac{3r+2}{4(1+r)^2}$.

Table 3. Sensitivity trends under Strategy GL.

Parameter	e	w	p	π_R^{GL}	π_M^{GL}
k	↓	↓	↓	↓	↑↓
r	↓	↑	↓	↓	↓

The results show that Strategy GL facilitates green investment by alleviating the manufacturer's liquidity constraint, while its effectiveness is governed by the green investment cost coefficient k and the financing rate r . As k increases, the manufacturer reduces green effort, leading to lower retail prices and weakened demand, which in turn reduces the retailer's profit. The manufacturer's profit is non-monotone in k : a moderate increase in k mitigates over-investment in greening, whereas a high k renders green investment excessively costly relative to its demand benefits. Moreover, an increase in r uniformly weakens the effectiveness of Strategy GL, as higher financing costs erode the incentives for both production and green investment.

4.1.3. Strategy CL

Strategy CL further introduces cost coordination: the retailer shares a fraction t of the manufacturer's green investment cost in addition to providing production financing. The retailer first chooses the

cost-sharing ratio t and the unit margin y , and the manufacturer then determines w and e . Demand remains $D_{CL} = 1 - p_{CL} + e_{CL}$, $p_{CL} = w_{CL} + y_{CL}$. The profit functions are

$$\pi_M^{CL} = (w_{CL} - c)D_{CL} - \frac{1}{2}ke_{CL}^2(1-t) - \left(cD_{CL} + \frac{1}{2}ke_{CL}^2(1-t)\right)r, \quad (4.5)$$

$$\pi_R^{CL} = (p_{CL} - w_{CL})D_{CL} - \frac{1}{2}ke_{CL}^2t + \left(cD_{CL} + \frac{1}{2}ke_{CL}^2(1-t)\right)r. \quad (4.6)$$

Lemma 3. Under Strategy CL, the manufacturer's equilibrium wholesale price and greening degree are denoted as $w_{CL}^* = \frac{(1+r)[(t-1)^2(k(1+r)+c(k(1+r)(3+4r)-3r-2))+3t(1+r)]}{-2+3r(-1+t)+4k(1+r)^2(-1+t)^2+3t}$ and $e_{CL}^* = \frac{(1-c)(r+1)(1-t)}{-2+3r(-1+t)+4k(1+r)^2(-1+t)^2+3t}$, respectively. The retailer's equilibrium retail price is given by $p_{CL}^* = \frac{-(1+2r)+c(1+r)(t-1)+k(c+3)(1+r)^2(t-1)^2+2t(1+r)}{-2+3r(-1+t)+4k(1+r)^2(-1+t)^2+3t}$.

Based on Lemma 3, the retailer and manufacturer's profits are $\pi_R^{CL} = \frac{(-1+c)^2k(1+r)^2(-1+t)^2}{-4+6r(-1+t)+8k(1+r)^2(-1+t)^2+6t}$ and $\pi_M^{CL} = \frac{(-1+c)^2k(1+r)^3(1+2k(1+r)(-1+t))(-1+t)^3}{2(-2+3r(-1+t)+4k(1+r)^2(-1+t)^2+3t)^2}$, respectively. The above equilibrium solutions are valid and feasible only if the technological parameter satisfies the critical threshold condition $k > \hat{k}_2 = \frac{1}{2(1+r)(1-t)}$.

For readability, the fully expanded expressions are reported in the Appendix, while the main text retains the compact forms above.

Corollary 2. Based on Lemma 2, Table 4 summarizes how the key decision variables change with the green investment cost coefficient k and financing rate r under Strategy GL. Specifically, when $0 < t < \hat{t}_2$, $\partial w_{CL}^*/\partial k < 0$ and $\partial \pi_r^{CL}/\partial k < 0$; when $0 < t < \hat{t}_4$, $\partial \pi_m^{CL}/\partial k < 0$ and $\partial e_{CL}^*/\partial t > 0$; when $\hat{t}_4 < t < \hat{t}_2$, $\partial \pi_m^{CL}/\partial k > 0$; and when $\hat{t}_2 < t < 1$, $\partial w_{CL}^*/\partial k > 0$, $\partial \pi_r^{CL}/\partial k > 0$, and $\partial \pi_m^{CL}/\partial k < 0$. With respect to t , $\partial w_{CL}^*/\partial t$ and $\partial \pi_r^{CL}/\partial t$ are positive for $0 < t < \hat{t}_5$ and negative for $\hat{t}_5 < t < 1$. Moreover, for $\hat{t}_4 < t < 1$, $\partial e_{CL}^*/\partial t < 0$ when $\hat{k}_2 < k < \hat{k}_6$, but $\partial e_{CL}^*/\partial t > 0$ when $k > \hat{k}_6$. Finally, $\partial \pi_m^{CL}/\partial t > 0$ for $0 < t < \hat{t}_6$, < 0 for $\hat{t}_6 < t < \hat{t}_2$, and > 0 again for $\hat{t}_2 < t < 1$, where $\hat{k}_2 = \frac{1}{2(1+r)(1-t)}$, $\hat{k}_6 = \frac{1}{4(1+r)^2(1-t)^2}$, $\hat{t}_2 = \frac{3r+2}{3r+3}$, $\hat{t}_4 = \frac{2r+1}{2r+2}$, $\hat{t}_5 = \frac{3r+1}{3r+3}$, and $\hat{t}_6 = \frac{r}{r+1}$.

Table 4. Effects of key parameters on equilibrium outcomes under Strategy CL.

Parameter	e_{CL}	w_{CL}	p_{CL}	π_R^{CL}	π_M^{CL}
k	↓	↓↑	↓	↓↑	↓↑↓
t	↑ / ↓↑	↑↓	↑	↑↓	↑↓↑

The results show that Strategy CL facilitates green investment by alleviating the manufacturer's liquidity constraint and reducing its effective green-cost burden, while its effectiveness is governed by the green investment cost coefficient k and the cost-sharing ratio t . As k increases, the responses of wholesale pricing and profit allocation vary with the level of cost sharing, leading to non-monotone changes in the retailer's and manufacturer's profits. The manufacturer's profit is non-monotone in k because cost sharing can either mitigate excessive green investment or amplify cost pressure, depending on the sharing level. Moreover, changes in t have non-monotone effects on both operational decisions and profit allocation, reflecting the trade-off between incentive provision and surplus redistribution under cost sharing.

4.2. Comparison analysis

Building on the equilibrium outcomes derived in Section 4.1, we next compare the three financing strategies to identify how they differ in shaping product greenness, pricing decisions, and profit allocation. This comparison addresses our second research question by clarifying the parameter regions in which each strategy dominates from the perspectives of the retailer, the manufacturer, and the supply chain as a whole.

Proposition 1. *The product greenness levels under Strategy GL and Strategy CL compare as follows:*

- (i) When $0 < t < \hat{t}_3$,
 - (a) if $\hat{k}_2 < k < \hat{k}_3$, then $e_{CL} < e_{GL}$;
 - (b) if $\hat{k}_3 < k < \hat{k}_5$, then $e_{GL} < e_{CL}$;
 - (c) if $\hat{k}_5 < k$, then $e_{CL} < e_{GL}$.

- (ii) When $\hat{t}_3 < t < \hat{t}_4$,
 - (a) if $\hat{k}_2 < k < \hat{k}_5$, then $e_{CL} < e_{GL}$;
 - (b) if $\hat{k}_5 < k$, then $e_{GL} < e_{CL}$.

- (iii) If $\hat{t}_4 < t < 1$ and $\hat{k}_2 < k$, then $e_{GL} < e_{CL}$,

$$\text{where } \hat{k}_2 = \frac{1}{2(1+r)(1-t)}, \hat{k}_3 = \frac{3r+2}{4(1+r)^2}, \hat{k}_5 = \frac{3(1+r)(1-t)-1}{4(1+r)^2(1-t)^2}, \hat{t}_3 = \frac{r}{3r+2}, \text{ and } \hat{t}_4 = \frac{r}{1+r}.$$

Proposition 1 shows that the relative performance of Strategy GL and Strategy CL in promoting product greenness is not monotone in either the green investment cost coefficient or the cost-sharing ratio. The underlying reason is that Strategy GL relaxes the manufacturer's financing constraint through dedicated green funding, whereas Strategy CL further redistributes part of the green investment burden to the retailer. When the cost-sharing ratio is low, the additional relief brought by Strategy CL is limited, and Strategy GL may generate a higher greenness level in some parameter regions. As the cost-sharing ratio increases, however, the burden transfer becomes more effective, and Strategy CL gradually dominates by providing stronger investment incentives. Consequently, Strategy CL is superior to Strategy GL only within specific parameter bands rather than over the entire feasible domain.

This result establishes the environmental benchmark for the subsequent comparisons. Since greenness affects both demand expansion and cost recovery, the ranking in Proposition 1 naturally shapes the wholesale-price and retail-price outcomes that follow. For managers, the implication is clear: cost sharing should be calibrated to the manufacturer's technological capability and financial pressure so that financing support can be translated into environmental improvement.

Proposition 2. *The equilibrium wholesale prices exhibit the following relationships:*

- (i) When $0 < t < \hat{t}_3$,
 - (a) if $\hat{k}_2 < k < \hat{k}_3$, then $w_{GL} < w_{CL} < w_{PL}$;
 - (b) if $\hat{k}_3 < k < \hat{k}_5$, then $w_{CL} < w_{PL} < w_{GL}$;
 - (c) if $\hat{k}_5 < k$, then $w_{PL} < w_{GL} < w_{CL}$.

- (ii) When $\hat{t}_3 < t < \hat{t}_4$,
- (a) if $\hat{k}_2 < k < \hat{k}_5$, then $w_{CL} < w_{PL} < w_{GL}$;
 - (b) if $\hat{k}_5 < k$, then $w_{PL} < w_{GL} < w_{CL}$.
- (iii) If $\hat{t}_4 < t < \hat{t}_1$ and $\hat{k}_2 < k$, then $w_{PL} < w_{GL} < w_{CL}$.
- (iv) If $\hat{t}_1 < t < \hat{t}_2$ and $\hat{k}_2 < k$, then $w_{PL} < w_{CL} < w_{GL}$.
- (v) If $\hat{t}_2 < t < 1$ and $\hat{k}_2 < k$, then $w_{CL} < w_{PL} < w_{GL}$.

Proposition 2 extends the greenness comparison and shows that the wholesale-price ranking across Strategy PL, Strategy GL, and Strategy CL is determined by how the financing arrangement reshapes the manufacturer's green investment incentives. The intuition is that wholesale pricing is the first channel through which financing benefits and investment costs are transmitted along the supply chain. Under Strategy GL, the manufacturer bears the full green investment burden and therefore has a stronger incentive to recover costs through the wholesale price. Under Strategy CL, by contrast, retailer participation may either ease the manufacturer's pricing pressure or, when greenness increases sufficiently, support a higher wholesale price through the enhanced green value of the product. This explains why the wholesale-price ordering changes across different regions of the cost-sharing ratio and the green investment cost coefficient.

Economically, the wholesale price is not merely a passive reflection of production cost, but a strategic response to the financing contract. The result also links back to Proposition 1: when Strategy CL delivers higher greenness, it may either compress or raise the wholesale price depending on whether cost relief or value enhancement is the dominant force. For managers, this means that wholesale pricing should be assessed jointly with the induced greenness outcome, rather than interpreted in isolation.

Proposition 3. *The equilibrium retail prices exhibit the following relationships:*

- (i) When $0 < t < \hat{t}_3$,
- (a) if $\hat{k}_2 < k < \hat{k}_3$, then $p_{GL} < p_{CL} < p_{PL}$;
 - (b) if $\hat{k}_3 < k < \hat{k}_5$, then $p_{CL} < p_{PL} < p_{GL}$;
 - (c) if $\hat{k}_5 < k$, then $p_{PL} < p_{GL} < p_{CL}$.
- (ii) When $\hat{t}_3 < t < \hat{t}_4$,
- (a) if $\hat{k}_2 < k < \hat{k}_5$, then $p_{CL} < p_{PL} < p_{GL}$;
 - (b) if $\hat{k}_5 < k$, then $p_{PL} < p_{GL} < p_{CL}$.
- (iii) If $\hat{t}_4 < t < 1$ and $\hat{k}_2 < k$, then $p_{PL} < p_{GL} < p_{CL}$.

Proposition 3 follows naturally from Proposition 2 and shows how the upstream pricing effects are ultimately passed through to the consumer market. The retail price is jointly determined by the wholesale price and the product's greenness, so any change in the financing arrangement affects the final market price through both cost-recovery and demand-expansion channels. In regions where Strategy CL generates stronger greenness without creating excessive residual cost pressure, it can support a relatively competitive retail price. In other regions, however, the higher investment burden associated

with Strategy CL may outweigh its demand-expansion effect, leading to a higher retail price than under Strategy GL or Strategy PL.

This indicates that greenness and price competitiveness do not necessarily move in the same direction. The pricing result therefore reinforces the message from the previous proposition: a contract that improves environmental performance is not necessarily the one that yields the lowest retail price. From a managerial perspective, the financing strategy should be selected together with the downstream pricing objective, because the preferred choice depends on whether the retailer targets market expansion or premium positioning.

Proposition 4. *The comparison outcomes for the profit of the retailer are presented below:*

(i) When $0 < t < \hat{t}_3$,

(a) if $\hat{k}_2 < k < \hat{k}_3$, then $\pi_r^{GL} < \pi_r^{CL} < \pi_r^{PL}$;

(b) if $\hat{k}_3 < k < \hat{k}_5$, then $\pi_r^{CL} < \pi_r^{PL} < \pi_r^{GL}$;

(c) if $\hat{k}_5 < k$, then $\pi_r^{PL} < \pi_r^{GL} < \pi_r^{CL}$.

(ii) When $\hat{t}_3 < t < \hat{t}_4$,

(a) if $\hat{k}_2 < k < \hat{k}_5$, then $\pi_r^{CL} < \pi_r^{PL} < \pi_r^{GL}$;

(b) if $\hat{k}_5 < k$, then $\pi_r^{PL} < \pi_r^{GL} < \pi_r^{CL}$.

(iii) If $\hat{t}_4 < t < \hat{t}_1$ and $\hat{k}_2 < k$, then $\pi_r^{PL} < \pi_r^{GL} < \pi_r^{CL}$.

(iv) If $\hat{t}_1 < t < \hat{t}_2$ and $\hat{k}_2 < k$, then $\pi_r^{PL} < \pi_r^{CL} < \pi_r^{GL}$.

(v) If $\hat{t}_2 < t < 1$ and $\hat{k}_2 < k$, then $\pi_r^{CL} < \pi_r^{PL} < \pi_r^{GL}$,

where $\hat{t}_1 = \frac{3r+1}{3r+2}$ and $\hat{t}_2 = \frac{3r+2}{3r+3}$.

Proposition 4 further translates the pricing effect into the retailer's payoff and shows that the retailer's profit ranking reflects the combined impact of greenness, pricing, and direct financing exposure. The intuition is that Strategy CL benefits the retailer only when the demand increase generated by higher greenness is large enough to offset the cost of sharing the manufacturer's green investment. When the green investment cost coefficient is low or moderate and the sharing ratio is well-calibrated, Strategy CL can generate substantial demand growth and thus outperform Strategy GL. When the cost burden becomes too large or the sharing ratio is not aligned with the manufacturer's capability, however, Strategy GL becomes more attractive because it preserves the green-demand benefit while avoiding direct cost participation. Strategy PL remains the least profitable whenever green demand is sufficiently valuable, because it does not create the demand uplift associated with product greenness.

This result suggests that retailers should not automatically prefer the most interventionist contract. Instead, Strategy CL should be adopted only when the manufacturer's green investment capability is sufficiently strong and the retailer's cost participation can be converted into a meaningful demand gain; otherwise, Strategy GL offers a more robust profit-maximizing alternative. The retailer's decision, therefore, should be made in conjunction with the greenness and pricing effects identified in the preceding propositions, rather than on the basis of cost sharing alone.

Proposition 5. *The comparison outcomes for the profit of the manufacturer are presented below:*

(i) If $\hat{k}_2 < k < \hat{k}_7$, then $\pi_m^{CL} < \pi_m^{PL} < \pi_m^{GL}$.

(ii) If $\hat{k}_7 < k < \hat{k}_8(r, t)$, then $\pi_m^{PL} < \pi_m^{CL} < \pi_m^{GL}$.

(iii) If $\hat{k}_8(r, t) < k$, then $\pi_m^{PL} < \pi_m^{GL} < \pi_m^{CL}$,

where $\hat{k}_7 = \frac{3(1+r)(1-t)-1}{8(1+r)^2(t-1)^2((2r+1)-2t(1+r))}$, and the cumbersome full expression of $\hat{k}_8$ is relegated to the Appendix for brevity.

Proposition 5 completes the comparison by shifting attention to the manufacturer and shows that green financing is generally beneficial, but the relative advantage of Strategy GL and Strategy CL depends critically on technological capability. The intuition is that Strategy GL provides financing relief while preserving the manufacturer's decision autonomy, whereas Strategy CL further reduces the manufacturer's effective green-cost burden by shifting part of the investment cost to the retailer. In the low-to-intermediate range of the green investment cost coefficient, Strategy GL dominates because it improves liquidity without introducing additional coordination pressure. As the green investment cost coefficient increases, however, Strategy CL becomes more attractive because retailer participation increasingly offsets the manufacturer's residual burden and allows the manufacturer to capture more value from the resulting market expansion. Once the cost coefficient exceeds the switching threshold $\hat{k}_8(r, t)$, Strategy CL becomes the most profitable strategy.

This pattern implies an evolutionary governance implication for manufacturers. They should initially rely on Strategy GL when green capability is still developing, and then move toward Strategy CL as technological maturity increases and shared investment becomes a more effective value-creation mechanism. In this sense, the transition from Strategy GL to Strategy CL is not merely a financing adjustment, but a strategic shift from liquidity support to co-investment coordination.

5. Fairness concern

In our basic model, we assume that all decision-makers are fully rational and strive to maximize their own economic profits. However, in practice, the perception of fairness is a crucial psychological factor that can significantly influence firm behavior and the stability of collaborative relationships. Extensive research in behavioral operations suggests that participants who perceive themselves as unfairly disadvantaged may take actions to reduce inequality, even if it lowers their own absolute payoff. This phenomenon is particularly salient in hierarchical supply chains where a powerful leader (e.g., a retailer) interacts with a dependent follower (e.g., a capital-constrained manufacturer). The follower, often bearing disproportionate risk and investment burden, is highly sensitive to profit disparity and may exhibit strong fairness concerns [35, 36]. These concerns can distort operational decisions, such as investment levels and pricing, ultimately impacting supply chain efficiency and green performance.

Motivated by this evidence, our study extends the basic model to incorporate the manufacturer's fairness concern. To formalize this behavioral aspect, we adapt the established inequity aversion framework to our context. Following recent modeling approaches in sustainable supply chain management [27], we define the utility functions for both members as follows:

$$U_M = \pi_M - a(\pi_R - \pi_M), \quad (5.1)$$

$$U_R = \pi_R, \quad (5.2)$$

where U_M and U_R represent the utility of the manufacturer and the retailer, respectively. π_M and π_R denote their monetary profits, as defined in the basic model. a ($a \geq 0$) is the manufacturer's fairness concern coefficient. A larger a indicates a higher degree of aversion to earning less than the retailer.

The manufacturer's utility U_M decreases as the profit gap ($\pi_R - \pi_M$) widens, capturing its dissatisfaction with disadvantageous inequality. The retailer remains purely profit-maximizing ($U_R = \pi_R$), consistent with its role as the Stackelberg leader. The decision sequence remains identical to the basic model, but the manufacturer's objective is now to maximize U_M . When $a = 0$, the model reduces to the standard profit-maximizing case analyzed in Section 4.1.

5.1. Comparison analysis

This subsection compares the equilibrium results considering the manufacturer's fairness concern.

Proposition 6. *The comparison outcomes for the degree of product greening considering the manufacturer's fairness concern are as follows:*

(i) When $0 < t < \hat{t}_5$,

(a) if $\hat{k}_2 < k < \hat{k}_9$, then $\tilde{e}_{GL} < \tilde{e}_{CL}$;

(b) if $\hat{k}_9 < k < \hat{k}_{10}$, then $\tilde{e}_{CL} < \tilde{e}_{GL}$;

(c) if $\hat{k}_{10} < k$, then $\tilde{e}_{GL} < \tilde{e}_{CL}$.

(ii) When $\hat{t}_5 < t < \hat{t}_4$,

(a) if $\hat{k}_2 < k < \hat{k}_{10}$, then $\tilde{e}_{CL} < \tilde{e}_{GL}$;

(b) if $\hat{k}_{10} < k$, then $\tilde{e}_{GL} < \tilde{e}_{CL}$.

(iii) If $\hat{t}_4 < t < \hat{t}_6$ and $\hat{k}_2 < k$, then $\tilde{e}_{GL} < \tilde{e}_{CL}$.

(iv) If $\hat{t}_6 < t < 1$ and $\hat{k}_2 < k$, then $\tilde{e}_{CL} < \tilde{e}_{GL}$,

where $\hat{t}_5 = \frac{r(a+r+ar-2a^2r+1)}{(a+1)(r+1)(2a+3r+6ar+2)}$, $\hat{t}_6 = \frac{a+r+ar-2a^2r+1}{(r+1)(-2a^2+a+1)}$, $\hat{k}_9 = \frac{(a+1)(2a+3r+6ar+2)}{4(a+r+2ar+1)^2}$, and $\hat{k}_{10} = \frac{(a+1)(2a+3r+2-3t(1+r+2ar)-6at)}{4(a+r-t+2ar-2at-tr-2art+1)^2}$.

Proposition 6 reveals that fairness concern alters the environmental comparison between Strategy GL and Strategy CL by introducing a relational dimension into the evaluation of cost sharing. The intuition behind this result is that, in the benchmark setting, cost sharing mainly reduces the manufacturer's residual green-cost burden, whereas fairness concern leads the manufacturer to assess whether the retailer's participation represents genuine joint commitment or merely partial financial relief. When the sharing ratio is low, Strategy CL does not sufficiently correct the perceived imbalance, and Strategy GL may still induce a higher greenness level because it preserves the manufacturer's autonomy. As the sharing ratio increases, however, Strategy CL becomes more credible as a cooperative arrangement and gradually strengthens the manufacturer's incentive to invest in green upgrading. Accordingly, Strategy CL dominates Strategy GL only within specific parameter bands rather than uniformly over the entire feasible domain. This result suggests that cost sharing should be designed as balanced co-investment rather than as the largest possible subsidy, because its behavioral value lies in transforming green upgrading into a jointly governed project.

Proposition 7. *The equilibrium product greenness $\tilde{e}_{GL}$ is compared with the no-fairness benchmark e_{GL} as follows:*

- (i) *If $\hat{k}_1 < k < \hat{k}_9$, then $\tilde{e}_{GL} < e_{GL}$;*
- (ii) *If $\hat{k}_9 < k < \hat{k}_3$, then $e_{GL} < \tilde{e}_{GL}$;*
- (iii) *If $\hat{k}_3 < k$, then $\tilde{e}_{GL} < e_{GL}$.*

Proposition 7 reveals that fairness concern does not uniformly suppress green investment under Strategy GL. The intuition behind this result is that green investment under Strategy GL is affected not only by financing relief, but also by the manufacturer's perception of how green value is distributed between the two parties. When the green-cost burden is low, the manufacturer may reduce greenness because it perceives that the retailer captures a disproportionate share of the green value while the manufacturer still bears the investment responsibility. In the intermediate region, fairness concern can instead stimulate greenness, because additional green effort strengthens the manufacturer's bargaining position and supports greater value appropriation through the wholesale price. When the green-cost burden becomes high, financing pressure again dominates and fairness concern discourages green investment. This result implies that Strategy GL is financially effective but behaviorally incomplete. For managers, the implication is that Strategy GL should be accompanied by transparent premium-sharing rules, long-term procurement commitments, or other relational safeguards, especially when the supplier is both capital constrained and sensitive to payoff imbalance.

Proposition 8. *The equilibrium product greenness $\tilde{e}_{CL}$ is compared with the no-fairness benchmark e_{CL} as follows:*

- (i) *When $0 < t < \hat{t}_4$,*
 - (a) *if $\hat{k}_2 < k < \hat{k}_{10}$, then $\tilde{e}_{CL} < e_{CL}$;*
 - (b) *if $\hat{k}_{10} < k < \hat{k}_5$, then $e_{CL} < \tilde{e}_{CL}$;*
 - (c) *if $\hat{k}_5 < k$, then $\tilde{e}_{CL} < e_{CL}$.*
- (ii) *If $\hat{t}_4 < t < \hat{t}_9$ and $\hat{k}_2 < k$, then $e_{CL} < \tilde{e}_{CL}$.*
- (iii) *When $\hat{t}_9 < t < 1$,*
 - (a) *if $\hat{k}_2 < k < \hat{k}_{13}$, then $\tilde{e}_{CL} < e_{CL}$;*
 - (b) *if $\hat{k}_{13} < k$, then $e_{CL} < \tilde{e}_{CL}$,*

where $\hat{t}_9 = \frac{a + 2r + 4ar + 1}{4a + 2r + 4ar + 2}$, and $\hat{k}_{13} = \frac{a + 1}{4(r + 1)(1 - t)(a + r - t + 2ar - 2at - rt - 2art + 1)}$.

Proposition 8 reveals that Strategy CL can either amplify or weaken green investment once fairness concern is introduced, depending on the cost-sharing ratio and the green investment cost coefficient. The intuition behind this result is that fairness concern makes the manufacturer evaluate not only the financial relief from cost sharing, but also whether the arrangement preserves autonomy and signals credible cooperation. When the sharing ratio is low, the manufacturer still bears most of the green investment burden, so fairness concern tends to suppress greenness except in the intermediate region where additional effort can improve the bargaining position. When the sharing ratio is moderate,

fairness concern raises greenness throughout the feasible region because the retailer's participation credibly reduces disadvantageous inequality and turns the contract into a reciprocal green-investment arrangement. When the sharing ratio becomes too high, however, the manufacturer may perceive excessive dependence on the retailer, which weakens the motivational effect of cost sharing. This result suggests that the behavioral value of Strategy CL does not come from maximizing the sharing ratio, but from selecting a level that makes the manufacturer feel supported while still preserving responsibility for green innovation.

Proposition 9. *The comparison outcomes for the retailer's utility considering fairness concern are as follows:*

(i) When $0 < t < \hat{t}_7$,

(a) if $\hat{k}_2 < k < \hat{k}_9$, then $U_R^{GL} < U_R^{CL} < U_R^{PL}$;

(b) if $\hat{k}_9 < k < \hat{k}_{10}$, then $U_R^{CL} < U_R^{PL} < U_R^{GL}$;

(c) if $\hat{k}_{10} < k$, then $U_R^{PL} < U_R^{GL} < U_R^{CL}$.

(ii) If $\hat{t}_8 < t < \hat{t}_7$ and $\hat{k}_2 < k$, then $U_R^{PL} < U_R^{CL} < U_R^{GL}$.

(iii) If $\hat{t}_7 < t < 1$ and $\hat{k}_2 < k$, then $U_R^{CL} < U_R^{PL} < U_R^{GL}$,

where $\hat{t}_7 = \frac{2a + 3r + 6ar + 2}{6a + 3r + 6ar + 3}$ and $\hat{t}_8 = \frac{2a + 4r + 12ar + 12ar^2 + 8a^2r + a^2 + 3r^2 + 12a^2r^2}{(2a + 1)(r + 1)(2a + 3r + 6ar + 2)}$.

Proposition 9 reveals that fairness concern changes the retailer's financing preference by introducing a behavioral layer into the usual demand–cost trade-off. The intuition behind this result is that the retailer remains profit-maximizing, but now anticipates the manufacturer's fairness-sensitive response when choosing among the three strategies. Strategy PL may still be preferred when the green-cost burden is low, because green-oriented intervention adds little commercial value. Strategy GL becomes attractive in the intermediate region because it activates green investment without exposing the retailer to direct cost-sharing obligations. Strategy CL becomes optimal only when the green-cost burden is high enough for shared investment to induce substantial green effort and market expansion. Accordingly, the retailer's preference is contingent rather than fixed. This result suggests that a leading retailer should regard Strategy PL as a conservative baseline, Strategy GL as a liquidity-based green activation tool, and Strategy CL as a deeper coordination instrument, and should move across these instruments only when the supplier's green-cost burden and the market response to greenness justify a higher level of relational commitment.

Proposition 10. *The comparison outcomes for the manufacturer's utility considering fairness concern are as follows:*

(i) If $\hat{k}_2 < k < \hat{k}_{11}$, then $U_M^{CL} < U_M^{PL} < U_M^{GL}$;

(ii) If $\hat{k}_{11} < k < \hat{k}_{12}$, then $U_M^{PL} < U_M^{CL} < U_M^{GL}$;

(iii) If $\hat{k}_{12} < k$, then $U_M^{PL} < U_M^{GL} < U_M^{CL}$,

where $\hat{k}_{11} = \frac{(a+1)(2a+3r+2-3t(1+r+2ar)-6at)^2}{8(a+r-t+2ar-2at-tr-2art+1)^2(a+2r-2t+4ar-4at-2rt-4art+1)}$ and the cumbersome full expression of $\hat{k}_{12}$ is relegated to the Appendix for brevity.

Proposition 10 reveals that the manufacturer's utility ranking under fairness concern is governed by the trade-off among financing relief, autonomy preservation, and perceived payoff distribution. The intuition behind this result is that Strategy GL provides targeted financing while allowing the manufacturer to retain control over green investment and pricing, whereas Strategy CL further reduces the effective green-cost burden by shifting part of the investment cost to the retailer. When the green-cost burden is limited, Strategy GL yields the highest utility because the manufacturer values autonomy more than additional cost relief. As the burden increases, Strategy CL first becomes better than Strategy PL and eventually dominates Strategy GL, indicating that cost sharing becomes acceptable only when it produces sufficiently large operational relief. This result implies that monetary attractiveness and behavioral acceptability need not coincide. For managers, the implication is that a viable Strategy CL contract should combine financial support with relational governance, including transparent cost accounting, credible benefit sharing, and long-term commitment.

The above trade-off structure gives rise to a critical threshold $\hat{k}_{12}$ that partitions the manufacturer's strategy preference across different cost regimes. In settings where the green-cost burden is relatively low, such as those involving incremental green investment like packaging optimization or minor process upgrades, the manufacturer tends to prefer Strategy GL due to autonomy preservation. In contrast, in settings where the cost burden becomes substantial, such as those requiring capital-intensive green technologies or regulatory compliance investment, Strategy CL becomes more attractive as cost sharing provides sufficient operational relief.

6. Numerical analyses

6.1. Parameter calibration and experimental design

The numerical analysis is designed to complement the analytical results and to examine whether the main comparative statics remain robust across economically meaningful parameter regimes. The benchmark values are selected to span representative levels of financing pressure, green-investment efficiency, cost-sharing intensity, and fairness concern, so as to validate the threshold structure derived in the theoretical analysis and to identify how the strategy ranking evolves across different operating environments.

The interest rate r captures the borrowing cost faced by the capital-constrained manufacturer. Since financing frictions are a central feature of supply chain finance, we consider $r \in \{0.3, 0.5\}$ to represent moderate and relatively severe financing pressure. This setting is consistent with the practice of using alternative financing-cost scenarios to test the robustness of equilibrium outcomes in capital-constrained supply chain models [10, 28].

The cost-sharing ratio t measures the retailer's participation in green investment. Prior studies on green supply chains show that cost-sharing contracts can improve greenness and coordination, but their effects depend critically on the sharing intensity. Accordingly, we set $t \in \{0.1, 0.4, 0.6, 0.8\}$ to cover low, medium, and high sharing regimes [9, 12, 26].

The green investment coefficient k governs the convex cost of greening and inversely reflects green-investment efficiency. Quadratic investment-cost functions are standard in the green supply chain literature, and k is commonly treated as a structural sensitivity parameter in numerical studies. We therefore examine $k \in \{0.8, 1.0, 2.0\}$, spanning relatively efficient, moderate, and inefficient green-investment environments [9, 12] and strong fairness concerns, respectively. This setting allows us to identify how behavioral preferences

reshape the relative attractiveness of the three financing strategies [22, 23].

The unit production cost is normalized to $c = 0.3$ to keep the exposition focused on the interaction among financing cost, green investment, and cost sharing. All benchmark scenarios satisfy the feasibility condition under Strategy CL, $k > \hat{k}_2 = \frac{1}{2(1+r)(1-t)}$.

6.2. Sensitivity analysis on product greenness

Figure 2 illustrates how financing rates r , green investment cost coefficient k , and cost-sharing ratios t jointly influence product greenness across different financing strategies.

Figure 2(a) shows that, when k and t are low, Strategy GL generates a positive green level at low interest rates. As r increases, however, greenness declines monotonically because higher financing costs weaken the manufacturer's incentive to invest in green effort. By contrast, Strategy CL is less sensitive to financing pressure: although its initial green level is slightly lower, the sharing arrangement gradually offsets the adverse effect of rising r , and Strategy CL eventually dominates Strategy GL. Figure 2(b) reveals a similar pattern. As t increases, the greenness of GL continues to decline with r , whereas Strategy CL becomes progressively more resilient because a larger sharing ratio lowers the manufacturer's effective green-cost burden. Figure 2(c) further indicates that, when k increases, Strategy CL consistently outperforms Strategy GL in greenness across all interest-rate levels, and the gap between the two strategies becomes more stable.

These results corroborate Proposition 1 and indicate that greenness is shaped by the interaction of financing pressure, investment cost, and cost sharing rather than by any single factor alone. The economic implication is clear: financing support can promote green investment, but its environmental effect remains limited when the manufacturer still bears most of the green-cost burden. From a managerial perspective, retailers who seek to stabilize and deepen green transformation should combine green lending with burden-sharing arrangements instead of relying on financing alone.

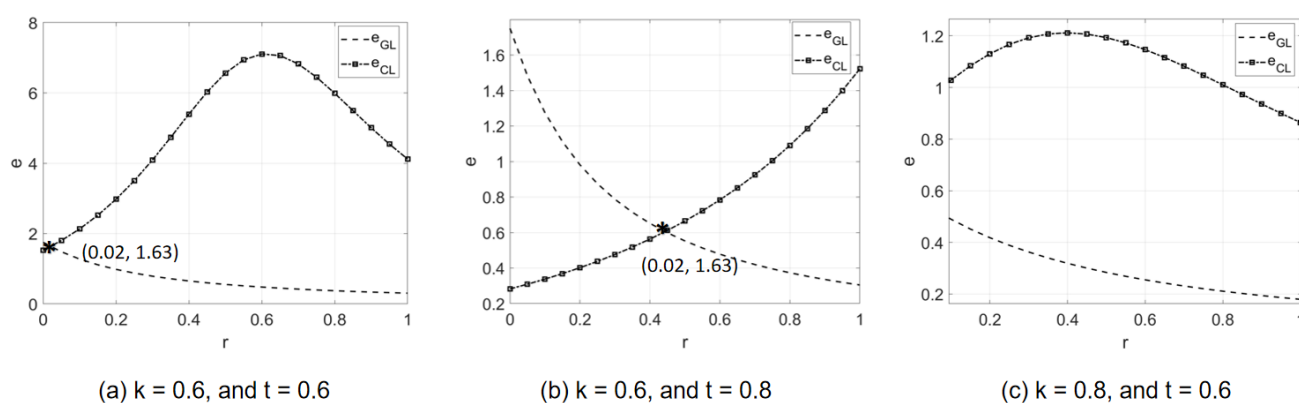


Figure 2. Comparison of product greenness across financing modes.

6.3. Sensitivity analysis on wholesale pricing

Figure 3 examines the joint effects of the cost-sharing ratio t and the green investment cost coefficient k on wholesale pricing. Strategies PL and GL exhibit horizontal patterns, as they are invariant to t , while

GL consistently commands a higher wholesale price than PL because the manufacturer must recover the full green-investment burden.

Figure 3(a) shows that, when $k = 1$, Strategy CL generates the highest wholesale price across feasible t values and follows an inverted-U pattern. At low sharing levels, the manufacturer transfers part of the green cost through a higher wholesale price; as t rises, retailer participation increasingly relaxes the manufacturer's pricing pressure and lowers the wholesale price.

Figure 3(b) shows that, when $k = 2$, Strategy CL still rises slightly and then declines with t , although the turning region shifts. In high-sharing regions, Strategy GL may dominate Strategy CL because the manufacturer under Strategy GL has to recover the full green cost through wholesale pricing.

These findings corroborate Proposition 2 and show that wholesale pricing is not a passive reflection of production cost, but a strategic response to the financing contract. The managerial implication is that cost sharing should be calibrated carefully: if it is too weak, it cannot relieve financing pressure; if it is too strong, it may suppress the manufacturer's markup incentive and weaken the intended coordination effect.

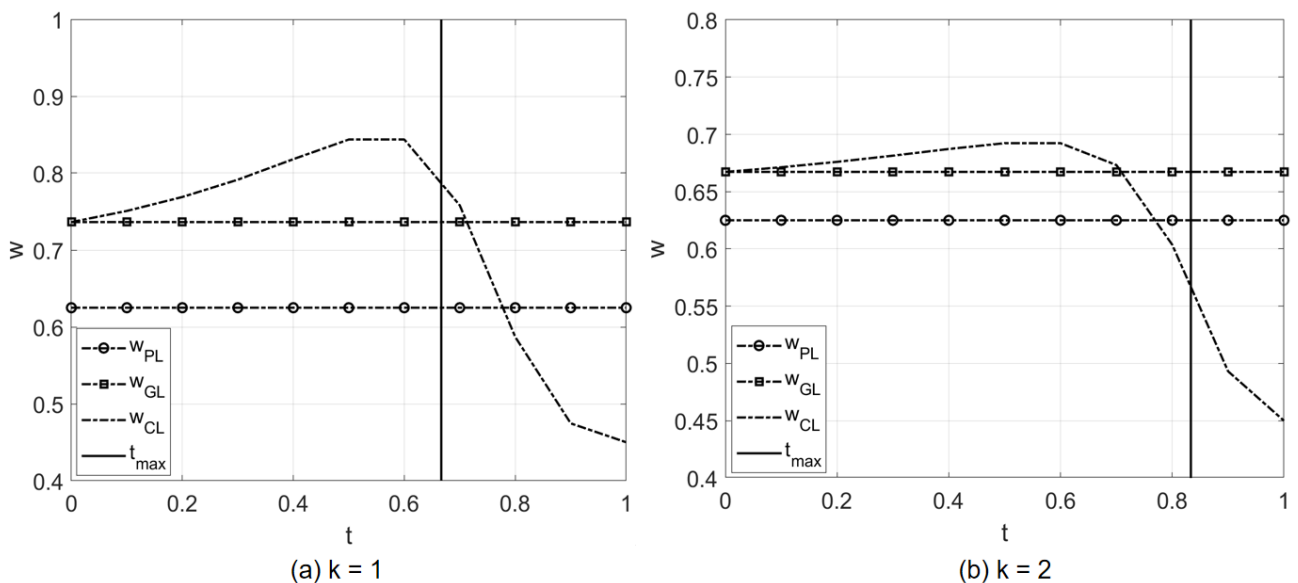


Figure 3. Comparison of wholesale prices across financing modes.

6.4. Sensitivity analysis on fairness concern intensity

Figures 4 and 5 depict the equilibrium utilities under the three financing strategies as the manufacturer's fairness concern coefficient a varies, with $t = 0.4$ and $t = 0.6$ used as representative moderate and high sharing levels. This setting highlights the interaction between fairness concern and cost sharing in determining the relative utility performance of the three strategies.

Figure 4 reports the retailer's utility. Under all three strategies, the retailer's utility decreases with a , indicating that stronger fairness concern on the manufacturer's side reduces the retailer's attainable payoff. When $t = 0.4$, Strategy CL consistently yields the highest retailer utility, followed by Strategy GL and then Strategy PL. At this sharing level, the demand expansion induced by cost-supported greening is sufficient to offset the retailer's sharing burden, so Strategy CL retains its payoff advantage as

fairness concern increases. When $t = 0.6$, however, the retailer's utility under Strategy CL declines much more sharply and eventually falls below that under Strategy GL and Strategy PL. The higher sharing burden then dominates the incremental demand benefit generated by greening. Thus, the retailer's preference for Strategy CL is contingent on a sufficiently moderate sharing level rather than on cost sharing per se.

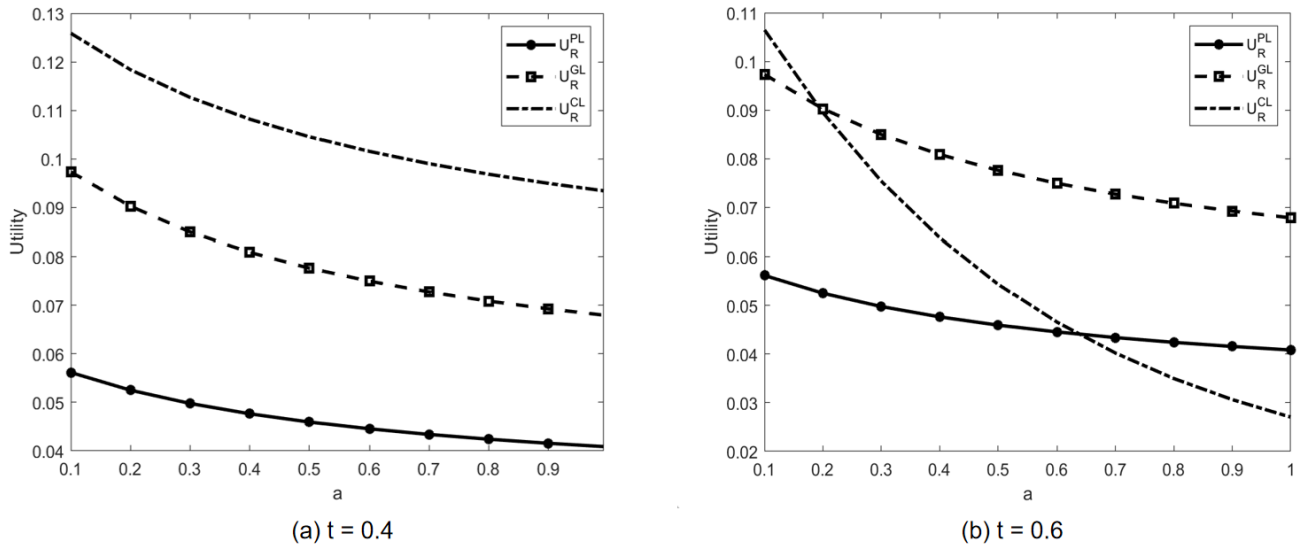


Figure 4. Comparison of retailer utility across financing strategies.

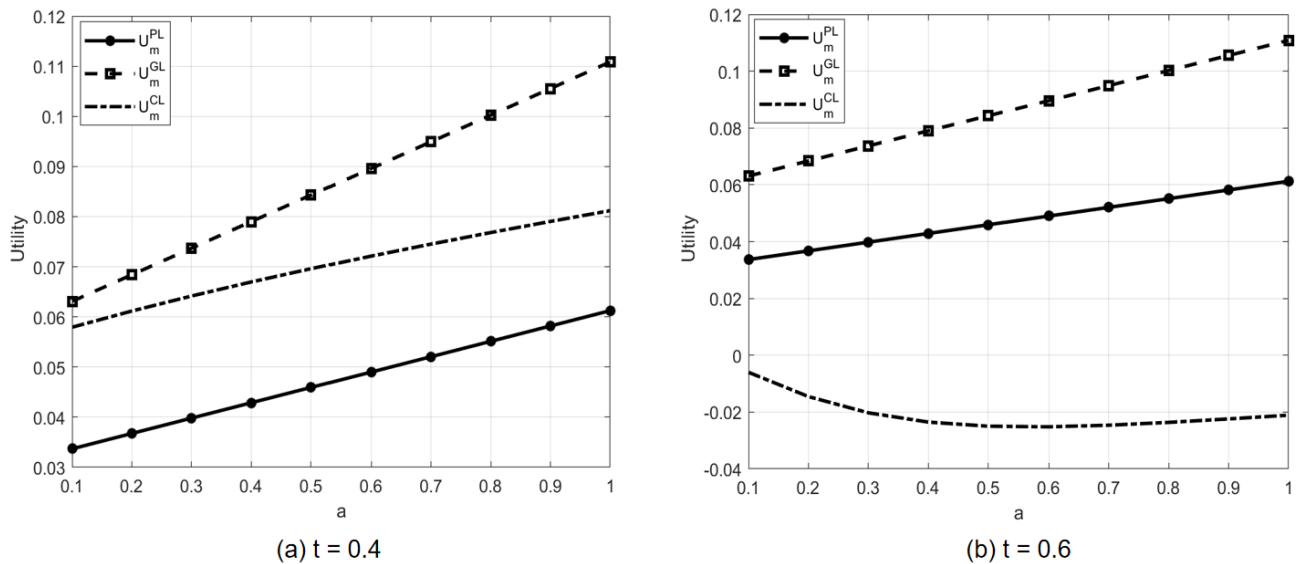


Figure 5. Comparison of manufacturer utility across financing strategies.

Figure 5 shows the manufacturer's utility. When $t = 0.4$, the manufacturer's utility increases with a under all three strategies, and Strategy GL consistently provides the highest utility. This suggests that, under moderate retailer participation, fairness concern makes the manufacturer more sensitive to payoff allocation and strengthens the relative attractiveness of financing arrangements that alleviate funding

pressure without constraining operational autonomy. Strategy GL is therefore particularly effective because it supports green investment while preserving the manufacturer's decision authority. When $t = 0.6$, the utility under Strategy CL becomes non-monotone and remains below those under Strategy PL and Strategy GL over most of the range. In this case, excessive retailer participation weakens the manufacturer's utility because the benefit of cost relief is offset by the perceived loss in surplus and autonomy. By contrast, Strategy GL remains comparatively stable, since it relaxes financing pressure without introducing additional coordination burden.

Taken together, these results indicate that fairness concern continuously reshapes the utility ranking across financing strategies, and that its effect is mediated by the cost-sharing ratio. This pattern is consistent with Propositions 9 and 10, which show that the effects of fairness concern on greenness and strategy preferences depend jointly on cost sharing, financing relief, and the distribution of decision rights. When sharing is moderate, Strategy CL preserves the retailer's payoff advantage, while Strategy GL remains the manufacturer's most stable option. When sharing is high, however, the additional contribution required from the retailer and the perceived loss of autonomy for the manufacturer jointly weaken the behavioral appeal of Strategy CL. Accordingly, the effectiveness of cost sharing depends not on maximizing retailer participation, but on calibrating the sharing ratio to reconcile financial support, payoff allocation, and behavioral incentives.

6.5. Sensitivity analysis on profit

6.5.1. Retailer's profit

Figure 6 analyzes how green investment cost coefficient k , cost-sharing ratio t , and interest rate r influence the retailer's optimal strategy selection.

Figure 6(a) shows that, in low- k and low- t regions, Strategy CL generates the highest retailer profit while Strategy GL yields the lowest. This occurs because limited cost sharing under Strategy CL alleviates the manufacturer's financing pressure while still stimulating demand through a modest greening effect, thereby achieving a favorable balance between demand expansion and cost burden. Under Strategy GL, by contrast, the manufacturer bears the full financing burden for both production and green investment, which drives up wholesale prices and compresses retailer profit. As k increases, the ranking changes across the threshold regions identified in Proposition 4, because the demand effect of greenness becomes strong enough to reshape the retailer's payoff.

Figure 6(b) further shows that, as r increases, the profit-dominant region of Strategy CL expands while that of Strategy GL contracts. This means that cost sharing becomes more valuable when financing conditions deteriorate, because it buffers the retailer against price escalation induced by the manufacturer's financing pressure.

These results are in line with Proposition 4 and suggest that retailers should not automatically favor the most interventionist contract. Strategy CL is attractive only when the induced demand gain is sufficiently large to offset the retailer's own sharing burden. Accordingly, retailers should adopt Strategy CL selectively, especially when the manufacturer's green capability and the market response to greenness are strong enough to justify deeper coordination.

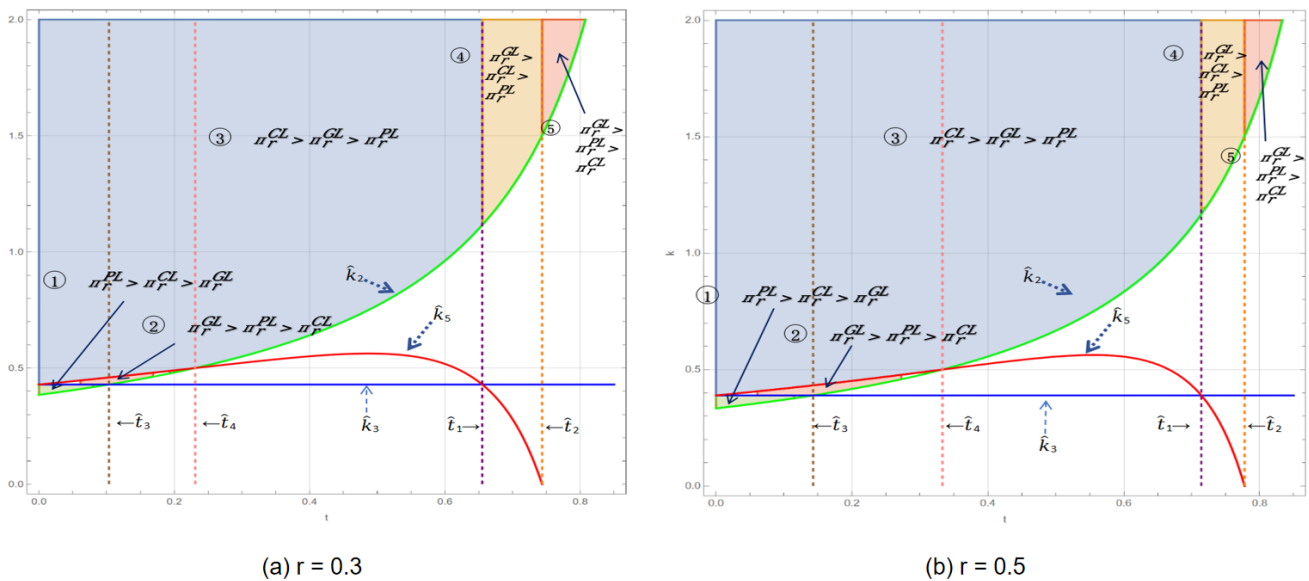


Figure 6. Comparison of retailer profits across financing modes.

6.5.2. Manufacturer's profit

Figure 7 examines how green investment cost coefficient k , cost-sharing ratio t , and interest rate r affect the manufacturer's strategy preferences.

Figure 7(a) indicates that, in low- k and low- t regions, Strategy CL yields the highest manufacturer profit while Strategy PL generates the lowest. This is because retailer participation directly reduces the manufacturer's effective green-cost burden and improves the profitability of green investment. Under Strategy GL, the manufacturer still bears the full green cost, so profits remain lower than under Strategy CL when green investment is expensive. As k increases, Strategy GL becomes more attractive in the intermediate region because it allows the manufacturer to benefit from green demand while preserving decision autonomy. Once k crosses the switching threshold, Strategy CL becomes dominant, since retailer participation generates enough cost relief to outweigh the loss of autonomy.

Figure 7(b) shows that, as r increases, the profit-dominant region of Strategy CL expands. This indicates that Strategy CL becomes more valuable when financing pressure intensifies, because cost sharing reduces the manufacturer's exposure to borrowing costs and improves the payoff from green investment.

These results corroborate Proposition 5. More broadly, Figure 7 suggests that the manufacturer's preference is governed by a trade-off among financing relief, pricing flexibility, and green-investment burden. Accordingly, manufacturers with weak green capability may initially rely on Strategy GL, but should move toward Strategy CL once green efficiency improves and retailer support becomes more valuable.

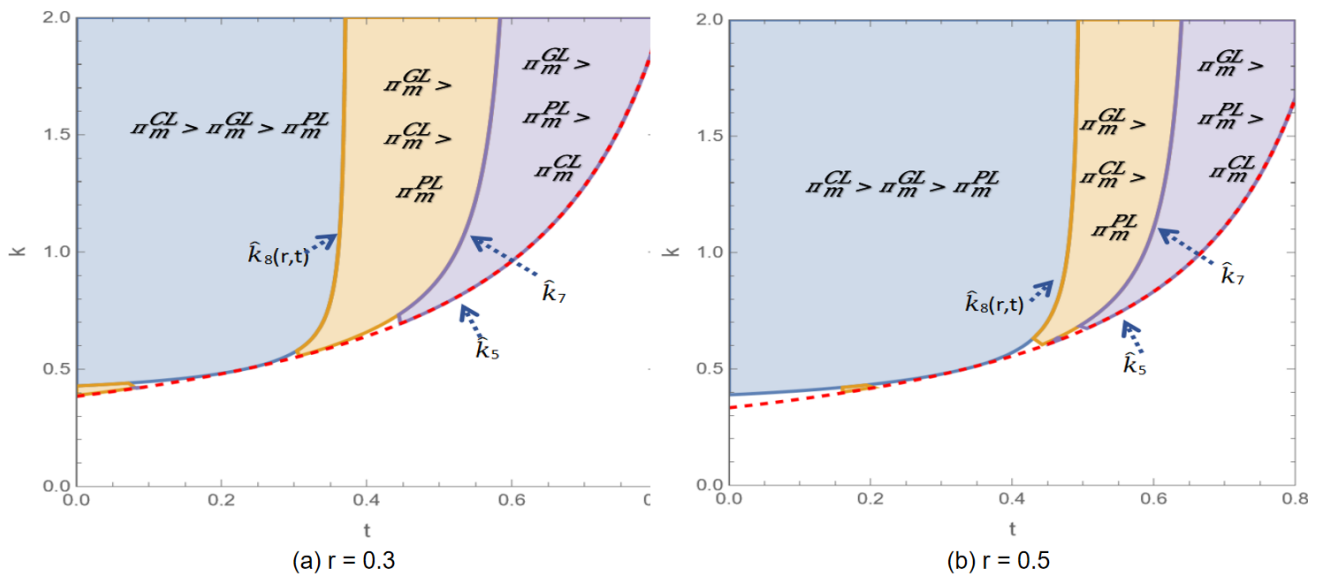


Figure 7. Comparison of manufacturer profits across financing modes.

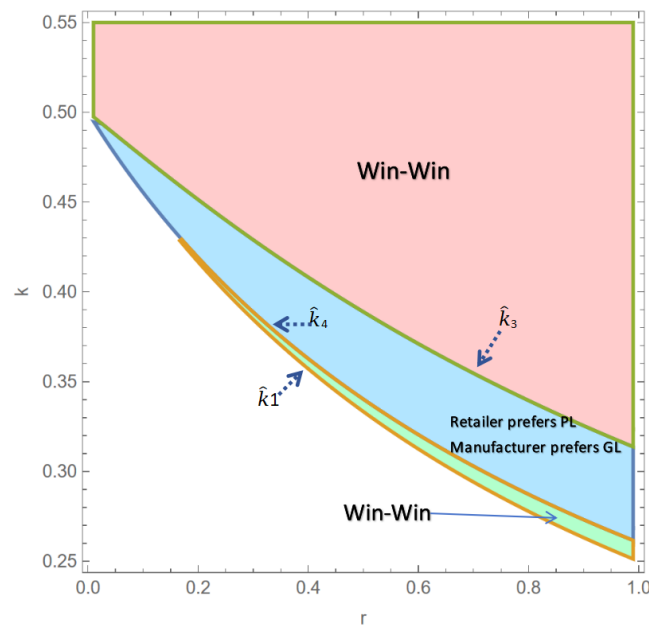


Figure 8. Win-win regions under Strategy PL vs. Strategy GL.

6.6. Win-win profit analysis

6.6.1. Strategy PL vs. Strategy GL

Figure 8 illustrates the profit alignment between Strategy PL and the Strategy GL. When k is low, both the retailer and the manufacturer prefer Strategy PL because green investment generates limited incremental value and financing costs outweigh the demand benefit of greenness. As k rises, a preference divergence emerges: the manufacturer begins to prefer Strategy GL because it enables green investment, while the retailer may still prefer Strategy PL because of concerns about cost pass through. When k

becomes sufficiently high, both parties prefer Strategy GL, creating a win-win region.

These results are consistent with the comparative logic in Propositions 4 and 5. They also indicate that green financing becomes mutually beneficial only when the underlying green technology is sufficiently productive. Thus, Strategy GL can serve as a transition instrument in the early stage of greening, but it requires adequate investment efficiency to become a stable coordination mechanism.

6.6.2. Strategy GL vs. Strategy CL

Figure 9 examines profit alignment between Strategy GL and Strategy CL. Figure 9(a) shows that at low t levels, both members prefer Strategy GL, as cost-sharing advantages remain unrealized while Strategy GL provides adequate green incentives. As t exceeds certain thresholds, preference divergence occurs: retailers favor Strategy CL for more stable supply chain relationships, while manufacturers prefer Strategy GL to maintain autonomy. When t exceeds $\hat{t}_1$, both prefer Strategy CL, indicating that high sharing ratios generate mutual benefits through coordination effects.

Figure 9(b) demonstrates that as k increases, the win-win region under Strategy CL expands substantially, confirming green investment efficiency as a critical enabler of supply chain coordination. These findings resonate with Propositions 3-5, indicating that the combination of high sharing ratios and technical efficiency can effectively align supply chain profit distribution and achieve synergistic benefits.

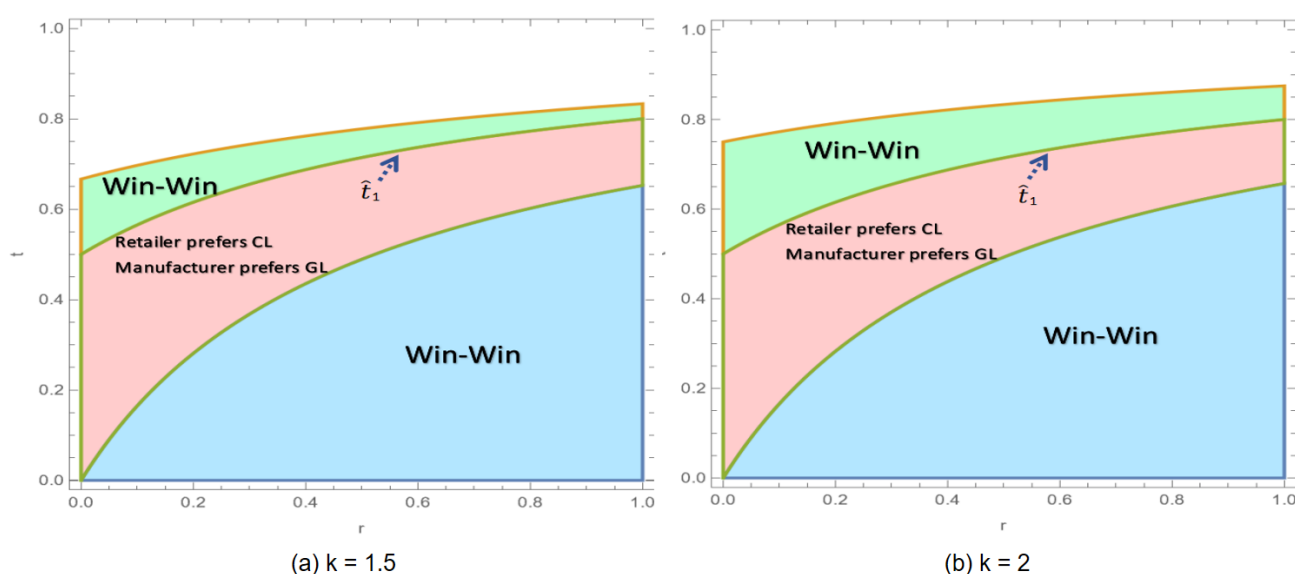


Figure 9. Win-win regions under Strategy GL vs. Strategy CL.

6.7. Sensitivity analysis on product greenness with fairness concern

Figure 10 delineates the parameter regions under Strategy CL where the manufacturer's fairness concern enhances or diminishes equilibrium product greenness relative to the no-fairness benchmark, as functions of the cost-sharing ratio t and the green investment cost coefficient k .

The numerical results reveal that the effect of fairness concerns on green investment is highly sensitive to both t and k . When t is relatively low, fairness concerns suppress greenness across the vast majority of the parameter space, with only a narrow intermediate range of k yielding higher greenness

under fairness. This pattern indicates that when the retailer's financial participation is limited, the manufacturer's sensitivity to profit disparity generally discourages environmental effort; only under specific intermediate efficiency conditions does the desire to improve the bargaining position override the disutility of inequity, prompting greater investment.

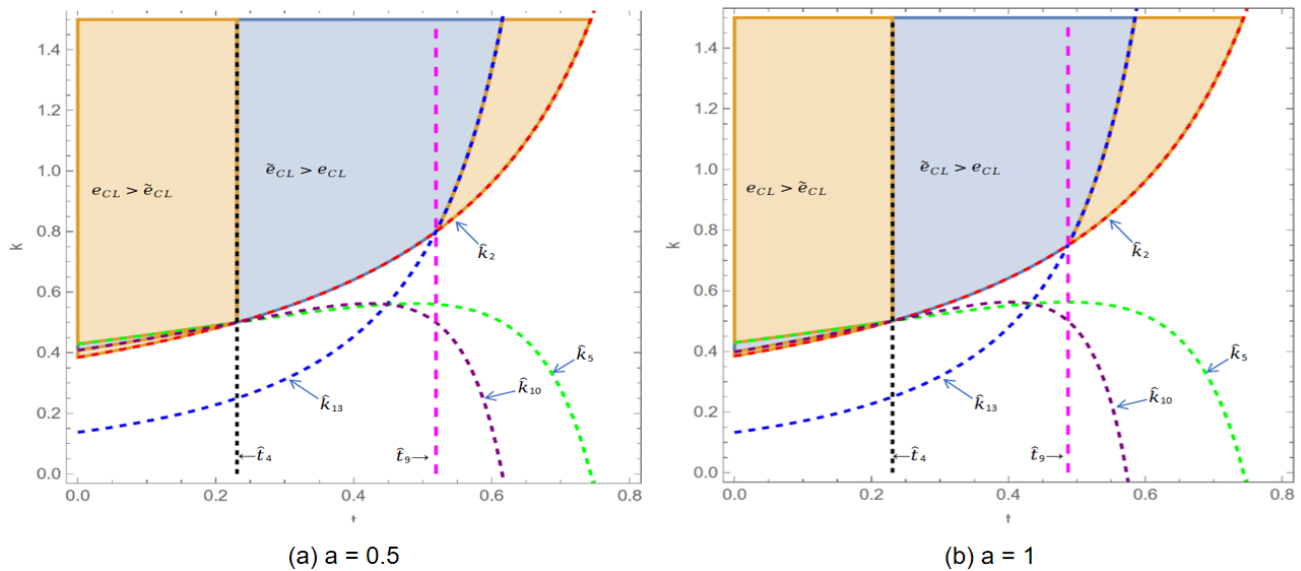


Figure 10. Comparison of greenness with and without fairness concerns under Strategy CL.

As t increases into the moderate range, the region where fairness concerns enhance greenness expands substantially. In this regime, the manufacturer perceives the retailer's contribution as sufficiently equitable, and fairness concerns translate into greater environmental effort across a wider spectrum of k . This finding confirms that adequate cost-sharing can transform fairness from a behavioral friction into a motivational force.

When t becomes excessively high, the pattern shifts again. Fairness concerns suppress greenness for lower values of k but enhance it when k is sufficiently low. This suggests that manufacturers with strong technological capabilities may view overly generous retailer participation as autonomy-reducing, dampening their incentive to invest despite the favorable financial terms.

These results validate Proposition 8, demonstrating that the directional effect of fairness concerns on green investment is contingent upon the interplay between contractual generosity and technological capability. For retailers, this implies that cost-sharing contracts must be carefully calibrated: insufficient sharing fails to offset the dampening effect of fairness concerns, while excessive sharing may inadvertently discourage investment from the most capable suppliers. The optimal sharing ratio lies in the moderate range where fairness concerns become a positive force for green innovation.

7. Conclusion and implications

7.1. Conclusion

This study examines a retailer-led green financing problem in a capital-constrained supply chain, where a financially strong retailer supports an upstream manufacturer in production and green investment. We compare three financing strategies within a unified Stackelberg framework: Strategy PL, Strategy

GL, and Strategy CL. We further incorporate the manufacturer's fairness concern to investigate how behavioral preferences affect green investment, pricing decisions, and strategy selection.

The results yield several key findings. First, Strategy PL serves as a basic liquidity-support mechanism, but it offers limited incentives for green transformation because it does not directly subsidize green investment. Second, Strategy GL is effective when the green investment cost coefficient k is relatively low, that is, when the marginal cost of improving product greenness is not severe. Under this condition, the manufacturer can convert financing support into green effort more effectively, and the retailer can benefit from the induced demand expansion. Third, Strategy CL becomes more attractive when the retailer's cost-sharing ratio is appropriately calibrated and the manufacturer's green-cost burden is sufficiently high for shared investment to create meaningful relief. In this case, Strategy CL not only enhances product greenness and bilateral profits, but also provides stronger resilience to financing-cost shocks.

The fairness extension shows that the manufacturer's fairness concern is not merely a behavioral detail; it materially changes the effectiveness of green financing contracts. When the manufacturer is fairness-sensitive, the value of cost sharing depends not only on financial relief, but also on whether the arrangement is perceived as equitable and cooperative. As a result, the relative performance of Strategy GL and Strategy CL becomes parameter-dependent rather than universal. Overall, the choice of financing strategy should be based on the joint consideration of the green investment cost coefficient, financing cost, cost-sharing intensity, and fairness preferences.

7.2. Managerial implications

The findings provide several practical implications for managers in manufacturing, retailing, and emerging green industries.

For capital-constrained manufacturers, especially SMEs in equipment manufacturing, consumer goods, automotive parts, and industrial components, the main issue is not only access to capital, but also the fit between financing mode and the stage of green transition. When the firm faces severe liquidity pressure and the green investment cost coefficient is relatively high, Strategy GL is a more suitable entry mechanism because it supports green upgrading without requiring the manufacturer to bear the full cost alone. As the green-cost burden becomes more manageable, Strategy CL becomes more attractive because retailer participation can further reduce the effective burden of green investment and improve commercial returns.

For retailers, the choice between Strategy GL and Strategy CL should depend on the product category and market positioning. In fast-moving consumer goods, apparel, and household products, where price competition is strong and green attributes are visible but not always dominant, Strategy GL can activate supplier greening with limited commitment. In categories with stronger green differentiation, such as premium food, green appliances, and certified sustainable products, Strategy CL is more suitable because it can create a deeper coordination mechanism and support longer-term value creation. However, retailers should avoid excessive cost sharing. A high sharing ratio does not necessarily improve performance; beyond a certain point, it may weaken the manufacturer's autonomy and reduce the behavioral effectiveness of the contract.

The implications are particularly relevant for new energy and low-carbon equipment industries, including photovoltaics, batteries, electric vehicles, and energy storage. These industries typically require substantial upfront R&D, process upgrading, and certification investment. In such settings,

Strategy GL can be used when suppliers are in an early transition phase and the green investment cost coefficient remains relatively low, while Strategy CL is more appropriate when suppliers already possess basic technological capability but still face financing bottlenecks and a high green-cost burden. This suggests that financing support should evolve with the supplier's technological maturity and cost pressure rather than remain fixed across all stages.

For policymakers and financial institutions, the results suggest that green financing support should be differentiated by the industry and capability stage. In manufacturing clusters dominated by SMEs, standard green credit can be used to address early liquidity constraints, while retailer-led cost sharing can be encouraged for firms with stronger innovation capacity and a lower green-cost burden. In strategic emerging industries, policy tools such as green certification support, tax incentives, and information disclosure can help reduce the friction between financing support and actual green investment. More generally, effective green financing should be designed not only to relieve liquidity pressure, but also to convert financial support into sustained green upgrading.

7.3. Limitations and future research directions

This study has several limitations that point to promising avenues for future research. First, the model assumes complete information symmetry among supply chain members. Future work can relax this assumption by introducing information asymmetry, hidden effort, or private knowledge about green capability, which would better reflect real-world contracting frictions.

Second, the present study focuses on a dyadic retailer-manufacturer structure. Future research can extend the analysis to multi-echelon supply chains involving banks, platforms, logistics firms, or government-backed green funds. Such extensions would enable a richer comparison of financing channels and coordination mechanisms.

Third, future studies can incorporate policy and market factors that are highly relevant in practice. Government green subsidies, carbon taxes, carbon trading, and emissions regulation may significantly reshape the relative attractiveness of Strategy PL, Strategy GL, and Strategy CL. Introducing these elements would make the model more policy-relevant and could generate stronger managerial guidance.

Fourth, demand uncertainty deserves further attention. In many green markets, consumer response to greenness is volatile and difficult to predict. Extending the model to stochastic demand, demand shocks, or dynamic market learning would improve the robustness of the conclusions, especially for sectors such as new energy vehicles, green appliances, and sustainable consumer goods.

Finally, behavioral research can be deepened by considering additional preference structures. The current model focuses on the manufacturer's fairness concern. Future work may explore retailer fairness concern, reciprocal preferences, and heterogeneous behavioral types on both sides of the channel. These extensions would provide a more complete understanding of how behavioral and financial frictions interact in green supply chain financing.

Author contributions

Fei Pan: Conceptualization, writing (original draft and review), methodology, funding acquisition, and supervision; Ming Liu: literature review, mathematical model formulation, equilibrium derivation, data curation, and comparative analysis; Yanqiu Zhu: writing-review and editing, numerical experiment design, results interpretation, funding acquisition, and supervision. All authors have read and agreed to

the submitted version of the manuscript.

Use of Generative-AI tools declaration

The authors declare that generative artificial intelligence tools were used solely to assist with language polishing, English expression refinement, and the preparation of selected initial drafts during the manuscript preparation process. The research questions, model design, mathematical derivations, equilibrium analysis, numerical analysis, interpretation of results, and final academic judgments were independently conducted and carefully verified by the authors. All authors assume full responsibility for the accuracy, integrity, and academic validity of the entire manuscript and its findings.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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