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Optimal Financing Schemes for E-Commerce Closed-Loop Supply Chains with Quality Uncertainty: Balancing Profitability and Environmental Impact

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Abstract

The rise of the circular economy and e-commerce has led to the emergence of e-commerce closed-loop supply chains (ECLSCs). In practice, investing in process innovation (PI) is key to improving profitability and competitiveness. However, manufacturers at the downstream of ECLSCs often face financial constraints and quality uncertainty of used products, while research on how to select financing strategies under these conditions remains limited. To explore the optimal financing scheme for the ECLSC, this study investigates two financing schemes: bank financing (BF) and FinTech platform financing (FPF), which offers a combination of debt financing (DF) and equity financing (EF). Some key findings are derived. For the ECLSC, the FPF scheme is more profitable when the unit manufacturing cost for new components exceeds the threshold or PI costs are relatively low. Additionally, the FPF performs better when the FPF interest rate is low and the DF ratio is high. The BF is more beneficial when consumer sensitivity to recycling prices or service is low. The FPF enables the ECLSC to achieve maximum profits and minimize environmental impact within a specific range. Furthermore, the financing models are extended to incorporate considerations of fairness, where the optimal financing scheme is primarily influenced by the manufacturing cost.

Keywords: e-commerce closed-loop supply chain; quality uncertainty; financing scheme; fairness concern

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1. Introduction

The circular economy (CE) is recognized as an essential strategy for continuously minimizing the environmental harm caused by inefficient production and consumption, while helping organizations achieve more resilient ESG (Environmental, Social, and Governance) indicators [1,2]. Closed-loop supply chains (CLSC), which exemplify the CE in action, have become acknowledged as a sustainable and low-carbon approach to production [3]. Companies such as Apple, Procter & Gamble, HP, Dell, and Xerox have successfully adopted this approach, reaping significant economic benefits from its implementation [4]. In recent years, the rapid development of e-commerce has attracted a growing number of consumers to shop online and participate in online recycling programs [5]. Thus, E-business has become a crucial component of CE practices worldwide, with some companies transitioning

their sales and recycling operations to online platforms, thereby establishing e-commerce closed-loop supply chains (ECLSC). By 2021, around 42,000 e-commerce enterprises in China focused on second-hand products [6].

With price transparency on internet platforms, consumer attention has turned to services such as logistics, home delivery, and quality inspection, making it essential for the platform to consider service levels comprehensively to stay competitive [7,8]. Moreover, platforms often secure higher profits due to their rule-setting authority and leverage economies of scale, which can lead to fairness concerns (FCs) among other members, as seen when the online recycling platform Re-Life shut down due to unfair profit distribution [9]. In this study, we extend our model by incorporating FCs to further explore its impact.

In practice, remanufacturing profitability and decision-making are significantly influenced by the quality of used products. Severely damaged products make remanufacturing very challenging or impossible. For instance, Caterpillar Group uses advanced technology to restore unusable core components to like-new conditions, maintaining market competitiveness. However, not all manufacturers have such capabilities, leading to a significant uncertainty due to the varying quality of recycled products [10]. Additionally, companies that succeed in the remanufacturing sector often invest heavily in process innovation to enhance their capabilities and reduce costs. For instance, Apple's Daisy robot optimizes the disassembly of old products, saving labor and time and lowering remanufacturing costs. Bosch developed a chip to assess the quality of components from its used products. Therefore, how remanufacturing and ECLSC performance are affected by uncertainty in used product quality and how remanufacturing enterprises decide on process innovation investment are the concerns of this study. Furthermore, these factors are often underexplored in other related ECLSC studies [6], highlighting the potential contribution of this research.

Capital constraints are a common challenge for SMEs, driven by pressures such as the need for process innovation and adapting to the evolving regulatory landscape, which increasingly mandates ESG compliance and reporting obligations [11]. Financial institutions provide various solutions to address these funding issues. For example, remanufacturing leader Caterpillar Group secured a USD 3 billion 9-month revolving credit line from banks [12]. Furthermore, with the development of digital technologies, some FinTech platforms provide financing solutions to capital-constrained supply chain participants to support their green and sustainable activities. Platforms like Carbon Chain (https://carbonchain.com) in the UK help SMEs in industries such as metals, oil and gas, mining, and agriculture to reduce carbon emissions and secure green financial support. Overall, FinTech platforms offer several advantages over traditional financing methods. They connect SMEs directly with investors through regulated digital platforms, thus reducing the need for intermediaries and lowering costs. Moreover, these platforms provide diverse financing options, such as debt and equity financing, which help reduce the risks for both SMEs and investors. The choice of financing scheme by a capital-constrained manufacturer as a downstream SME in the ECLSC, based on profit performance and environmental impact, is key to balancing economic and sustainability goals, as ESG performance reflected in carbon emissions and energy use is increasingly viewed as a measure of corporate responsibility [13].

Based on the above descriptions and to fill the gap in the existing research, this study constructs an ECLSC consisting of an e-commerce platform (E-platform) and a capital-constrained manufacturer under the uncertainty of used product quality. The manufacturer can choose between traditional bank financing (BF) and innovative FinTech platform financing (FPF), which offers a combination of debt financing (DF) and equity financing

(EF) to address the challenge of insufficient funding for process innovation. We aim to explore the following research questions:

1. What are the optimal operational decisions and remanufacturing strategies for an ECLSC under scenarios with no financial constraints and different financing schemes, considering the uncertainty in the quality of used products?
2. How do the remanufacturing quality threshold and recycling service sensitivity coefficient impact the optimal decisions and profits?
3. For the manufacturer facing capital constraints, how should ECLSCs choose the appropriate financing scheme? Which financing scheme has a smaller environmental impact?
4. If the manufacturer exhibits FC behavior, what impact do FCs have on capital-constrained ECLSCs?

By addressing the questions outlined above, this study yields several major findings and contributions.

1. We consider the effects of various parameters on the profit of the ECLSC. Our comparative and numerical analyses reveal that the FPF is more favorable when the unit remanufacturing cost exceeds a certain threshold or PI costs are low. Additionally, the FPF performs better when the FPF scheme's interest rate is low and the DF ratio is high. Furthermore, when consumer sensitivity to recycling prices or service is low, the BF is the preferred choice. More importantly, the FPF enables the ECLSC to maximize economic benefits and minimize environmental damage within a certain range. By identifying the optimal financing schemes under different conditions, this research provides valuable insights that empower companies to effectively navigate financial constraints and strategically enhance profitability across diverse market environments, and place greater emphasis on minimizing environmental impact.
2. Unlike Qin, Chen, Zhang, and Ding [10], this study finds that higher remanufacturing quality thresholds reduce recycled product quantities and profits, emphasizing the need for better product design, fostering collaboration, and implementing policy incentives.
3. An increased consumer sensitivity to recycling services positively impacts the ECLSC and enables consumers to benefit from higher valuations of used products and improved services under certain conditions. This contrasts with Wang, et al. [14], who found it challenging to balance high recycling prices and service levels.
4. Manufacturers' FC behavior negatively affects both the recycling efficiency of the ECLSC and the profit of the E-platform. Although FCs are often considered harmful to efficiency and profitability [6,15], our findings reveal that, within certain ranges, an increase in the FC coefficient can actually lead to higher manufacturer profit. In such cases, the optimal financing scheme selection remains largely consistent with scenarios without FCs, with the influencing factor being the unit manufacturing cost, further validating the robustness of our previous results.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature. In Sections 3 and 4, we develop the ECLSC model framework and derive the optimal solutions under different financing schemes. Section 5 analyzes the impact of key parameters and compares the solutions, profits, and environmental impact under the BF and FPF schemes. In Section 6, we conduct numerical analyses to further explore the financing preferences of the overall ECLSC and the manufacturer. In Section 7, we extend the models by considering the FCs. Finally, Section 8 makes conclusions and provides corresponding managerial implications. All proofs are included in the Appendix A.

2. Literature Review

This section reviews research on online channels in CLSC and considers the quality of CLSC, PI, and supply chain financing, offering insights that shape this study's approach and direction.

2.1. Online Channels in CLSC

E-commerce has transformed CLSC operations, sparking interest in online and dual-channel models. Kong, et al. [16] optimized pricing and service levels to address channel conflicts in dual-channel CLSC networks. Jia, and Li [17] analyzed decisions considering platform fees and fulfillment costs. Jin, et al. [18] examined channel power structures in reverse supply chains, considering online and offline recycling competition. Wang, et al. [19] showed that reward–punishment mechanisms and altruistic preferences enhance the recycling service levels of the platform, quality, and quantity. Wang, Yu, Shen, and Jin [14] investigated optimal decisions under different sales and recycling models, considering the impact of these models and platform service levels on the CLSC. Cui, et al. [20] compared pricing strategies for recycling under extended warranty services on E-platforms. Barman [21] explored different incentive mechanisms to improve the environmental sustainability of eco-friendly products within the closed-loop structure of an ECLSC. Sun, et al. [22] develop a dual-objective robust optimization framework that simultaneously seeks to reduce total operating costs and carbon emissions in an ECLSC network.

Several studies have explored FC issues from profit gaps between online platforms and other entities. Qin, et al. [23] proposed a revenue-sharing contract to address fairness under information symmetry and asymmetry. Wang, Wang, Cheng, Zhou, and Gao [6] analyzed consumer preferences for remanufactured and new products and FC. Qin, Wang, Gao, and Liu [9] used a signaling model to identify conditions for genuine FC information sharing, reducing profit losses in ECLSCs. Xiao, et al. [24] examined the dual behavioral preferences of FC and risk aversion of the manufacturer in a dual-channel green supply chain.

Considering the growing importance of CLSCs in the digital economy and the potential challenges they face, this paper examines a fully online ECLSC, focusing on optimizing operations, recycling processes, and financing strategies under capital constraints. Meanwhile, we extend the research scenarios by incorporating the perspective of FC. Unlike previous studies that primarily focused on traditional offline or dual-channel CLSCs, or the work of Qin, Wang, and Gao [23] and Wang, Wang, Cheng, Zhou, and Gao [6] on ECLSC operational model selection and coordination issues, our study provides fresh insights. This research complements the existing CLSC literature and offers practical guidance for ECLSC companies operating under capital constraints.

2.2. The Consideration of Quality in CLSC

Scholars have explored the impact of product quality on consumer preferences and recycling in CLSC. El Saadany, and Jaber [25] showed that combining production and remanufacturing is optimal when recycling rates depend on price and quality. Cai, et al. [26] studied pricing and production for high- and low-quality components. Taleizadeh, et al. [27] examined pricing strategies, quality levels, and sales efforts in dual-channel CLSCs. Zhang, et al. [28] studied pricing, quality, and revenue-sharing for defective and end-of-life products in dual-channel CLSCs. Feng, et al. [29] considered competition among new, remanufactured, and refurbished products with subsidies. Qin, Chen, Zhang, and Ding [10] examined quality uncertainty in engineering machinery recycling and its impact on remanufacturing decisions. Guo, and Chen [30] considered the quality uncertainty of recycled products and explored the scope of government subsidies.

However, most studies assume that homogeneous used products meet remanufacturing standards. Research on the impact of quality uncertainty on recycling efficiency is limited, except for Qin, Chen, Zhang, and Ding [10] and Guo, and Chen [30]. This study extends the existing literature by examining the effects of used product quality uncertainty on recycling efficiency within online recycling channels. Furthermore, we explore the manufacturer's PI activities in response to this quality uncertainty.

2.3. Process Innovation

PI is vital for boosting demand, reducing costs, and improving supply chain performance [31]. Reimann, et al. [32] found that PI strategies in forward supply chains do not directly apply to remanufacturing, with high innovation costs favoring decentralized decision-making. Guo, et al. [33] explore how technology investment in green production and remanufacturing, supported by dual government subsidies, influences optimal decision-making and enhances the performance of a green closed-loop supply chain in an e-commerce environment. Chai, et al. [34] studied PI's impact on green product CLSC performance, identifying optimal strategies in cooperative and non-cooperative contexts. Yang, et al. [35] analyzed the role of government subsidies in promoting technological progress. Niu, and Shen [36] explored manufacturers' PI decisions under knowledge spillovers and differing absorptive capacities. Sun, et al. [37] highlight how technology-driven innovations in logistics and supply chains enhance operational efficiency while creating significant societal and sustainability impacts. Pu, et al. [38] proposed a dynamic optimal control model that integrates PI and low-carbon efforts under the dual-carbon policy framework, considering the impact of knowledge accumulation. Qian, et al. [39] explored how upstream and downstream firms determine optimal PI strategies under the interaction between product innovation and PI, and examined how this interaction influences operational decisions.

While the existing research emphasizes PI's role in supply chain sustainability and efficiency, it often assumes firms have sufficient capital, neglecting the significant financial constraints many SMEs face. This study addresses this gap by exploring optimal financing schemes for capital-constrained ECLSCs pursuing PI.

2.4. Supply Chain Financing

In recent years, supply chain financing has rapidly developed, addressing SMEs' financing issues and expanding banking services. Several studies have explored various financing models, focusing on their impact on operational decisions [40–44]. Emerging technologies like the internet and cloud computing have introduced new financing methods and platforms. Wang, et al. [45] examined how E-platform financing and bank credit affect online retailers. Yi, et al. [46] studied agricultural supply chains with small farmers and financing platforms, finding that the platform encourages BF when production costs are high. Reza-Gharehbagh, et al. [47] analyzed green product development in SME supply chains using FinTech platforms. Zhang, et al. [48] developed a CLSC model with online equity crowdfunding, determining the optimal equity transfer ratio. Verma, and Mishra [49] investigated how financing options such as TCF and BF contribute to improving the sustainability and performance of the CLSC under government subsidies.

Building on previous research, this study compares traditional BF and innovative FPF within ECLSCs. It identifies conditions for the optimal use of each scheme and offers actionable recommendations. Furthermore, we extend the models by incorporating FC considerations. Table 1 summarizes the gaps in existing research and highlights the contributions of this study.

Table 1. Comparison with related literature.

Related Literature	SC Structure	Sales Channel	Recycling Channel	Quality of Used Products	Platform Service	PI	Capital Constraint	FC
Reimann, Xiong, and Zhou [32]	CLSC	Offline	Offline	Fixed		√		
Guo, Yu, and Gen [33]	Forward	Online/Offline	Offline	Fixed		√		
Yang, Tang, and Zhang [35]	Forward	Offline	Offline	Fixed		√		
Wang, Yu, Shen, and Jin [14]	CLSC	Online/Offline	Online/Offline	Fixed	√			
Reza-Gharehbagh, Arisian, Hafezalkotob, and Makui [47]	CLSC	Offline	Offline	Fixed			√	
Cui, Zhou, Yu, and Khan [20]	CLSC	Offline	Offline	Fixed	√			
Qin, Chen, Zhang, and Ding [10]	CLSC	Offline	Offline	Uncertain				
Wang, Wang, Cheng, Zhou, and Gao [6]	CLSC	Online	Online	Fixed	√			√
Chen, Tian, Chan, Tang, and Che [44]	CLSC	Online	Online	Fixed			√	
Guo, and Chen [30] Qian, Ignatius, Chai, and Valiyaveettil [39]	CLSC	Offline	Offline	Uncertain				
Barman [21]	Forward	Offline	Offline	Fixed		√		
Verma, and Mishra [49]	CLSC	Offline	Offline	Fixed			√	
This study	√	Online	Online	Uncertain	√	√	√	√

3. Problem Description

Motivated by downstream manufacturers' frequent financial constraints in ECLSCs, this study considers an ECLSC system composed of an E-platform and a risk-neutral, capital-constrained manufacturer (Figure 1), with both parties aiming to maximize profits. The E-platform provides product sales and recycling services, charging commissions for these. The manufacturer sells products and collects used ones via the E-platform, remanufacturing those meeting quality standards. To improve efficiency, the manufacturer also invests in PI to reduce remanufacturing costs.

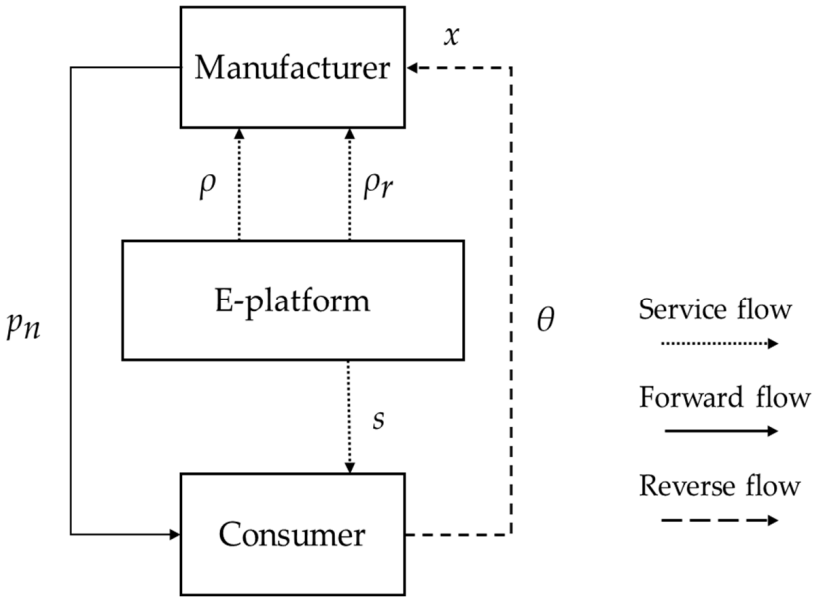


Figure 1. The schematic of the ECLSC.

The specific decision sequence is shown in Figure 2. The E-platform, benefiting from economies of scale and rule-making advantages [7], acts as the leader and first decides on the sales commission ρ, the commission for recycling used products ρ_r, and the platform recycling service level s. Subsequently, the follower manufacturer determines the PI level x, the sales price of new products p_n, and the quality-based value coefficient of used products θ, which in turn determines the recycling price of used products.

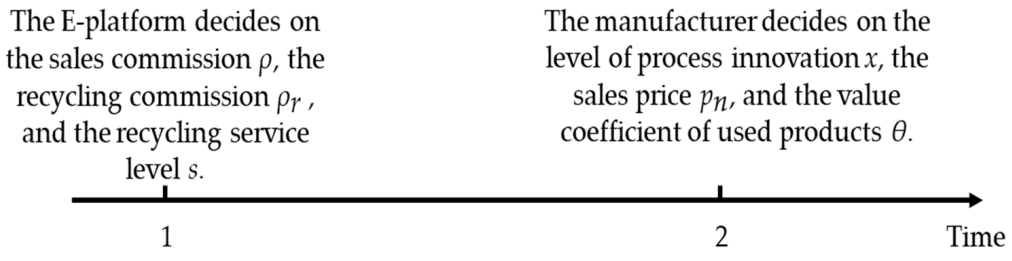


Figure 2. The decision sequence.

Table 2 presents the relevant parameters and their definitions used in this study. To facilitate a deeper analysis of the model, we make the following assumptions:

Table 2. Notations and their definitions.

Notations	Definitions
Decision variables	
ρ	The sales commission.
ρ_r	The recycling commission.
s	The platform recycling service level.
x	The PI level.
p_n	The sales price of new products.
θ	The quality-based value coefficient of used products.
Parameters	
α	The market size of the product.
β	The sales price sensitivity coefficient.
η	The recycling price sensitivity coefficient.
ϕ	The recycling service level sensitivity coefficient.
p_r	The recycling price.
f	The fixed payment.
q	The quality level of the used product, q, follows a uniform distribution of [0, 1].
q_0	The quality threshold for used products that can be remanufactured.
c_n/c_r	The unit cost of manufacturing/remanufacturing.
H	The PI cost coefficient.
L	The manufacturer's loan size.
r_b/r_f	The financing interest rate for the bank/FinTech platform, $r_b/r_f \in (0, 0.1)$.
ψ	The DF ratio.
Π_P	The expected profit of the E-platform.
Π_M	The expected profit of the manufacturer.
Π_T	The expected overall profit of the ECLSC.
Indexes	
Superscript N, B, F	Model NC, BF, FPF.

Assumption 1. *The manufacturer sells products via the E-platform, which charges a per-unit commission ρ on sales (this type of fee structure is common in practice, as seen with Amazon) and ρ_r on recycled products. The E-platform enhances consumer participation in recycling through services like appraisals, inspections, and at-home pickup. These services incur a cost of $\frac{1}{2}Ks^2$ $(K > 0)$, where s is the service level and the cost coefficient K is normalized to 1 [6,14,50].*

Assumption 2. *Although companies like Apple, Samsung, Huawei, and Amazon actively promote recycling and resale globally, CLSC integration rarely influences consumer behavior or sales [51]. Following related studies, this research assumes products consist of a single component, with new and recycled parts being identical in function and appearance [48,52]. The manufacturer can use new parts at a cost of c_n or remanufacture using recycled parts from used products that exceed the quality threshold q_0, which is more cost-effective $(c_n > c_r)$. For simplicity, we set c_r to 0 [53].*

Assumption 3. *According to Wang, Yu, Shen, and Jin [14] and Zhang, Meng, and Xie [48], the recycling quantity of used products is $D_r = \eta p_r + \phi s$ $(\eta, \phi > 0)$, where η is the recycling price sensitivity coefficient and ϕ is the service level sensitivity coefficient. The recycling price p_r, paid by the manufacturer, is expressed as $p_r = f + \theta q$ $(q > 0)$, where θ is the value coefficient of the used product and q is the quality level. A higher product quality q results in a higher recycling price. To simplify, the stochastic variable q is assumed to follow a standard uniform distribution $q \sim U(0, 1)$ based on historical data [10]. The manufacturer remanufactures used products whose quality exceeds the threshold q_0, and, for generality, let fixed payment $f = 0$.*

Assumption 4. *The demand function for the product is* $D = \alpha - \beta p_n$ $(\alpha, \beta > 0)$*, where* α *represents the market size of the product and* β *represents the sales price sensitivity coefficient [48]. To ensure non-negative results, it is assumed that* $\alpha > \beta c_n$*.*

Assumption 5. *The manufacturer endeavors to carry out PI activities during the remanufacturing phase, such as improving production processes, implementing technological innovations, and upgrading equipment, which do not involve product design. The PI level is represented by* x*. Through PI, the cost of remanufacturing can be reduced by* x*, while the investment cost is* $\frac{1}{2}Hx^2$ $(H > 0)$*, where* H *is the PI cost coefficient [34,54].*

Assumption 6. *As SMEs often rely on financing to support the implementation of innovative ideas, it is assumed that the manufacturer has no restrictions on daily operating capital. In contrast, the capital for process innovation is limited. This assumption is widely adopted in the existing literature [44,55–57]. Specifically, the manufacturer's internal funds available for process innovation are denoted by* M*, and the required loan amount is* $L = \left\{\frac{1}{2}Hx^2 - M\right\}^+$*. For analytical tractability and without loss of generality, we set* $M = 0$*. The manufacturer can address the funding issue through two schemes: BF and FPF.*

4. Model Formulation and Solution

In this section, we develop three models: a benchmark model where the manufacturer faces no financial constraints, the BF model, and the FPF model. We analyze the optimal decisions of the E-platform and the manufacturer under these different scenarios.

4.1. Model Without Capital Constraint (NC)

Given the uncertainty about the quality of used products, the expected profit function of the E-platform is as follows:

$$\Pi_P^N = \rho^N\left(\alpha - \beta p_n^N\right) + \rho_r^N \int_{q_0}^1 ((\theta^N q)\eta + \phi s^N)dq - \frac{1}{2}s^{N2} \tag{1}$$

Here, the first term represents the commission income from product sales, the second term represents the commission income from recycling used products, and the third term represents the platform's recycling service cost.

Given the uncertainty in the quality of used products, the expected profit function of the manufacturer without financial constraints is as follows:

$$\begin{aligned}\Pi_M^N = &\left(p_n^N - c_n - \rho^N\right)\left(\alpha - \beta p_n^N - \int_{q_0}^1 (\eta(\theta^N q) + \phi s^N)dq\right)\\ &+\left(p_n^N - -\rho_r^N - \int_{q_0}^1 (\theta^N q)dq - \rho^N + x^N\right)\int_{q_0}^1 (\eta(\theta^N q) + \phi s^N)dq - \tfrac{1}{2}Hx^{N2}\end{aligned} \tag{2}$$

In Equation (2), the first term represents the income from manufacturing using new components, the second term represents the income from remanufacturing, and the third term represents the cost of PI.

Proposition 1. *Given that* $H > \frac{2\eta^2}{-4\eta + (-1+q_0)^2\phi^2}$ *and* $\eta > \frac{(-1+q_0)^2\phi^2}{4}$*, the optimal solutions under the model where the manufacturer has no financial constraints are as follows:* $s^{N*} = \frac{H\eta\phi c_n(-1+q_0)}{2\eta(-2H+\eta)+H\phi^2(-1+q_0)^2}$, $\rho_r^{N*} = \frac{\eta(-2H+\eta)c_n}{2\eta(-2H+\eta)+H\phi^2(-1+q_0)^2}$, $\rho^{N*} = \frac{\alpha-\beta c_n}{2\beta}$, $p_n^{N*} = \frac{1}{4}\left(\frac{3\alpha}{\beta} + c_n\right)$, $\theta^{N*} = \frac{2Hc_n(\eta-\phi^2(-1+q_0)^2)}{(2\eta(-2H+\eta)+H\phi^2(-1+q_0)^2)(-1+q_0^2)}$, $x^{N*} = -\frac{\eta^2 c_n}{2\eta(-2H+\eta)+H\phi^2(-1+q_0)^2}$.

The optimal outcomes are summarized in Table 3.

Table 3. Optimal solutions.

Variables	Solutions
(a) NC model	
s^{N*}	$\frac{H\eta\phi c_n(-1+q_0)}{2\eta(-2H+\eta)+H\phi^2(-1+q_0)^2}$
ρ_r^{N*}	$\frac{\eta(-2H+\eta)c_n}{2\eta(-2H+\eta)+H\phi^2(-1+q_0)^2}$
ρ^{N*}	$\frac{\alpha-\beta c_n}{2\beta}$
p_n^{N*}	$\frac{1}{4}\left(\frac{3\alpha}{\beta}+c_n\right)$
θ^{N*}	$\frac{2Hc_n(\eta-\phi^2(-1+q_0)^2)}{(2\eta(-2H+\eta)+H\phi^2(-1+q_0)^2)(-1+q_0^2)}$
x^{N*}	$\frac{-\eta^2 c_n}{2\eta(-2H+\eta)+H\phi^2(-1+q_0)^2}$
Π_P^N	$\frac{1}{8}(\frac{(\alpha-\beta c_n)^2}{\beta}-\frac{4H\eta^2c_n^2}{2\eta(-2H+\eta)+H\phi^2(-1+q_0)^2})$
Π_M^N	$\frac{1}{16}(\frac{(\alpha-\beta c_n)^2}{\beta}+\frac{8H(2H-\eta)\eta^3c_n^2}{(-4H\eta+2\eta^2+H\phi^2(-1+q_0)^2)^2})$
Π_T^N	$\frac{1}{16}(\frac{3\alpha^2}{\beta}-6\alpha c_n+c_n^2(3\beta+\frac{8H\eta^2(6H\eta-3\eta^2-H\phi^2(-1+q_0)^2)}{(-4H\eta+2\eta^2+H\phi^2(-1+q_0)^2)^2}))$
D^N	$\frac{1}{4}(\alpha-\beta c_n)$
$D_r{}^N$	$\frac{H\eta^2c_n}{4H\eta-2\eta^2-H\phi^2(-1+q_0)^2}$
(b) BF model	
s^{B*}	$\frac{H\eta\phi c_n(-1+q_0)(1+r_b)}{2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b)}$
ρ_r^{B*}	$\frac{H\eta\phi c_n(-1+q_0)(1+r_b)}{2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b)}$
ρ^{B*}	$\frac{\alpha-\beta c_n}{2\beta}$
p_n^{B*}	$\frac{1}{4}\left(\frac{3\alpha}{\beta}+c_n\right)$
θ^{B*}	$\frac{2Hc_n(\eta-\phi^2(-1+q_0)^2)(1+r_b)}{(-1+q_0^2)(2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b))}$
x^{B*}	$-\frac{\eta^2c_n}{2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b)}$
Π_P^B	$\frac{1}{8}(\frac{(\alpha-\beta c_n)^2}{\beta}+\frac{4H\eta^2c_n^2(1+r_b)}{-2\eta^2+H(4\eta-\phi^2(-1+q_0)^2)(1+r_b)})$
Π_M^B	$\frac{1}{16}(\frac{(\alpha-\beta c_n)^2}{\beta}+\frac{8H\eta^3c_n^2(1+r_b)(-\eta+2H(1+r_b))}{(2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b))^2})$
Π_T^B	$\frac{1}{16}(\frac{3\alpha^2}{\beta}-6\alpha c_n+c_n^2(3\beta+\frac{8H\eta^2(1+r_b)(-3\eta^2+H(6\eta-\phi^2(-1+q_0)^2)(1+r_b))}{(2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b))^2}))$
D^B	$\frac{1}{4}(\alpha-\beta c_n)$
$D_r{}^B$	$\frac{H\eta^2c_n(1+r_b)}{-2\eta^2+H(4\eta-\phi^2(-1+q_0)^2)(1+r_b)}$

Table 3. *Cont.*

Variables	Solutions
(c) FPF model	
s^{F*}	$\frac{H\eta\phi\psi c_n(-1+q_0)(1+r_f)}{2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f)}$
ρ_r^{F*}	$\frac{\eta c_n(\eta-2H\psi(1+r_f))}{2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f)}$
ρ^{F*}	$\frac{\alpha-\beta c_n}{2\beta}$
p_n^{F*}	$\frac{1}{4}\left(\frac{3\alpha}{\beta}+c_n\right)$
θ^{F*}	$\frac{2H\psi c_n(\eta-\phi^2(-1+q_0)^2)(1+r_f)}{(-1+q_0^2)(2\eta^2+H\psi(-4\eta+\phi^2(-1+q_0)^2)(1+r_f))}$
x^{F*}	$\frac{-\eta^2 c_n}{2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f)}$
Π_P^F	$\frac{1}{8}(\frac{\alpha^2}{\beta}-2\alpha c_n+c_n^2(\beta+\frac{4H\eta^2\psi(1+r_f)}{-2\eta^2+H\psi(4\eta-\phi^2(-1+q_0)^2)(1+r_f)}))$
Π_M^F	$\frac{1}{16}\psi(\frac{\alpha^2}{\beta}-2\alpha c_n+\beta c_n^2+\frac{8H\eta^3\psi c_n^2(1+r_f)(-\eta+2H\psi(1+r_f))}{(2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))^2})$
Π_T^F	$\frac{1}{16}(\frac{\alpha^2(2+\psi)}{\beta}-2\alpha(2+\psi)c_n+\frac{8H\eta^2\psi(1+r_f)(\eta^2(2+\psi)-2H\eta\psi(2+\psi)(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))}{(-2\eta^2+H\psi(4\eta-\phi^2(-1+q_0)^2)(1+r_f))^2}+c_n^2(\beta(2+\psi)-))$
D^F	$\frac{1}{4}(\alpha-\beta c_n)$
$D_r{}^F$	$\frac{H\eta^2\psi c_n(1+r_f)}{-2\eta^2+H\psi(4\eta-\phi^2(-1+q_0)^2)(1+r_f)}$

4.2. Bank Financing (BF)

Bank financing, a traditional external financing method, enables the capital-constrained manufacturer to address its funding needs. Some banks also support green innovation financing schemes. For instance, Unilever signed a EUR 500 million sustainability-linked loan agreement with three banks, incorporating its efforts to reduce greenhouse gas emissions, increase renewable energy use, and enhance water management into the agreement conditions [58].

Under the BF scheme, the manufacturer borrows $L^B = \frac{1}{2}Hx^{B2}$ from the bank. At the end of the sales period, the manufacturer is required to repay the bank $(1+r_b)L^B$. The expected profit functions of the E-platform and the manufacturer are as follows:

$$\Pi_P^B = \rho^B\left(\alpha-\beta p_n^B\right)+\rho_r^B\int_{q_0}^1((\theta^B q)\eta+\phi s^B)dq-\frac{1}{2}s^{B2} \tag{3}$$

$$\begin{aligned}\Pi_M^B &= \left(p_n^B-c_n-\rho^B\right)\left(\alpha-\beta p_n^B-\textstyle\int_{q_0}^1(\eta(\theta^B q)+\phi s^B)dq\right)\\ &+\left(p_n^B-\rho_r^B-\textstyle\int_{q_0}^1(\theta^B q)dq-\rho^B+x^B\right)\int_{q_0}^1(\eta(\theta^B q)+\phi s^B)dq-(1+r_b)\tfrac{1}{2}Hx^{B2}\end{aligned} \tag{4}$$

Proposition 2. *Given that* $H > \frac{2\eta^2}{(1+r_b)(4\eta-(-1+q_0)^2\phi^2)}$ *and* $\eta > \frac{(-1+q_0)^2\phi^2}{4}$, *the optimal solutions under the BF model are as follows:* $s^{N*} = \frac{H\eta\phi c_n(-1+q_0)(1+r_b)}{2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b)}$, $\rho_r^{N*} = \frac{H\eta\phi c_n(-1+q_0)(1+r_b)}{2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b)}$, $\rho^{N*} = \frac{\alpha-\beta c_n}{2\beta}$, $p_n^{N*} = \frac{1}{4}\left(\frac{3\alpha}{\beta}+c_n\right)$, $\theta^{N*} = \frac{2Hc_n(\eta-\phi^2(-1+q_0)^2)(1+r_b)}{(-1+q_0^2)(2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b))}$, $x^{N*} = -\frac{\eta^2 c_n}{2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b)}$.

The optimal outcomes are summarized in Table 3.

4.3. FinTech Platform Financing (FPF)

With the advent of FinTech, FinTech-based supply chain finance has emerged as an alternative funding source, enabling SMEs to secure financing through various FinTech platforms. At present, China's FinTech adoption rate is particularly high at 87%, significantly higher than the global average of 64%. In the United States, financial innovations such as online lending have proven beneficial for SMEs, offering substantial innovation and growth potential to provide more loans to SMEs [59,60]. Moreover, platforms like Crowdcube and Fundable have become well-known equity crowdfunding sources, supporting projects in emerging industries such as AI, electronics, and environmental protection [48].

Under FPF, the FinTech platform organizes and allocates funds raised from a group of investors to financing projects that support the manufacturer's process innovation investment. These funds are allocated by the FinTech platform across DF and EF schemes to support the project (Figure 3). Specifically, the manufacturer obtains a total financing amount L, of which a proportion ψL is provided through DF at an interest rate r_f, while the remaining $(1-\psi)L$ is provided through EF. At the end of the sales period, the manufacturer repays the principal and interest and shares the profits with the FinTech platform. The total returns received by the FinTech platform are subsequently distributed to investors according to pre-investment contractual agreements and investment shares [47].

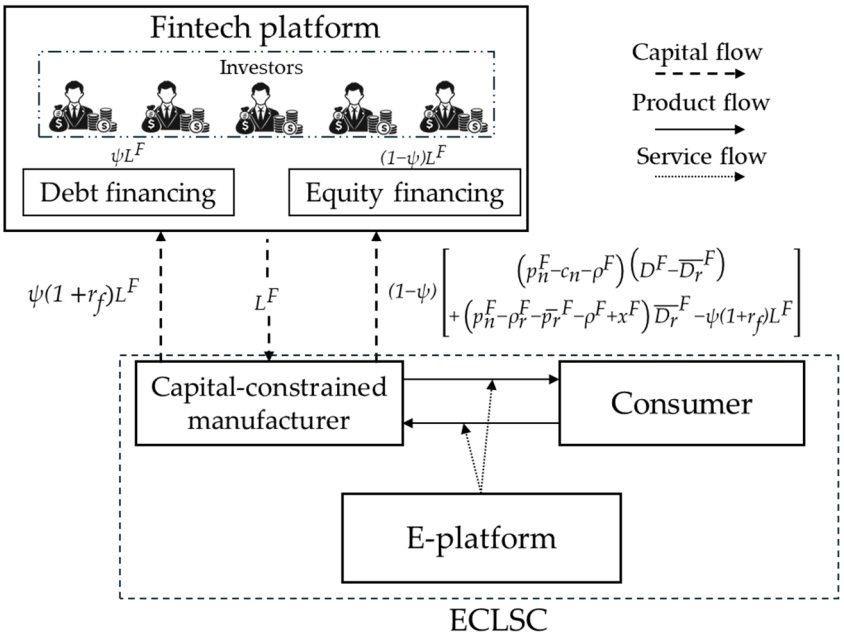


Figure 3. The schematic of FinTech platform financing.

Given the uncertainty in the quality of used products, the expected profit functions of the E-platform and the manufacturer are as follows:

$$\Pi_P^F = \rho^F\left(\alpha - \beta p_n^F\right) + \rho_r^F \int_{q_0}^1 ((\theta^F q)\eta + \phi s^F)dq - \frac{1}{2}s^{F2} \tag{5}$$

$$\Pi_M^F = \psi\left[\begin{array}{c}\left(p_n^F - c_n - \rho^F\right)\left(\alpha - \beta p_n^F - \int_{q_0}^1 \left(\eta\left(\theta^F q\right) + \phi s^F\right)dq\right) \\ +\left(p_n^F - \rho_r^F - \int_{q_0}^1 (\theta^F q)dq - \rho^F + x^F\right)\int_{q_0}^1 (\eta(\theta^F q) + \phi s^F)dq - \psi(1+r_f)\frac{1}{2}Hx^{F2}\end{array}\right] \tag{6}$$

Proposition 3. *Given that* $H > \frac{2\eta^2}{(1+r_f)(4\eta-(-1+q_0)^2\phi^2)\psi}$ *and* $\eta > \frac{(-1+q_0)^2\phi^2}{4}$, *the optimal solutions under the FPF model are as follows:* $s^{F*} = \frac{H\eta\phi\psi c_n(-1+q_0)(1+r_f)}{2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f)}$, $\rho_r^{F*} = \frac{\eta c_n(\eta-2H\psi(1+r_f))}{2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f)}$, $\rho^{F*} = \frac{\alpha-\beta c_n}{2\beta}$, $p_n^{F*} = \frac{1}{4}\left(\frac{3\alpha}{\beta} + c_n\right)$, $\theta^{F*} = \frac{2H\psi c_n(\eta-\phi^2(-1+q_0)^2)(1+r_f)}{(-1+q_0^2)(2\eta^2+H\psi(-4\eta+\phi^2(-1+q_0)^2)(1+r_f))}$, $x^{F*} = -\frac{\eta^2 c_n}{2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f)}$.

The optimal outcomes are summarized in Table 3. **Proof of Propositions A1–A3**: See Appendix A.1.

5. Model Analysis and Comparison

5.1. The Impact of Key Parameters

Corollary 1. *The impact of the remanufacturing quality threshold* q_0 *on optimal decisions and profits is as follows:* $\frac{\partial s^*}{\partial q_0} < 0$, $\frac{\partial \rho_r{}^*}{\partial q_0} < 0$, $\frac{\partial x^*}{\partial q_0} < 0$, $\frac{\partial D_r{}^*}{\partial q_0} < 0$; *if* $\eta > (-1+q_0)^2\phi^2$ *and* $-\frac{2\eta^2}{-4\eta+\phi^2(-1+q_0)^2} < H < \frac{2\eta^2(\phi^2(-1+q_0)^2+\eta q_0)}{4\eta^2 q_0+\phi^4(-1+q_0)^4 q_0-\eta\phi^2(-1+q_0)^2(-3+2q_0)}$, *then* $\frac{\partial\theta^{N*}}{\partial q_0} < 0$, *otherwise* $\frac{\partial\theta^{N*}}{\partial q_0} > 0$; *if* $\eta > (-1+q_0)^2\phi^2$ *and* $\frac{2\eta^2}{(4\eta-\phi^2(-1+q_0)^2)(1+r_b)} < H < \frac{2\eta^2(\phi^2(-1+q_0)^2+\eta q_0}{(4\eta^2 q_0+\phi^4(-1+q_0)^4 q_0-\eta\phi^2(-1+q_0)^2(-3+2q_0))(1+r_b)}$, *then* $\frac{\partial\theta^{B*}}{\partial q_0} < 0$, *otherwise* $\frac{\partial\theta^{B*}}{\partial q_0} > 0$; *if* $\eta > (-1+q_0)^2\phi^2$ *and* $\frac{2\eta^2}{(1+r_f)(4\eta-(-1+q_0)^2\phi^2)\psi} < H < \frac{2\eta^2(q_0\eta+(-1+q_0)^2\phi^2)}{(1+r_f)(4q_0\eta^2-(-1+q_0)^2(-3+2q_0)\eta\phi^2+(-1+q_0)^4 q_0\phi^4)\psi}$, *then* $\frac{\partial\theta^{F*}}{\partial q_0} < 0$, *otherwise* $\frac{\partial\theta^{F*}}{\partial q_0} > 0$. $\frac{\partial p_n{}^*}{\partial q_0} = 0$, $\frac{\partial D^*}{\partial q_0} = 0$, $\frac{\partial \rho^*}{\partial q_0} = 0$; $\frac{\partial \Pi_P}{\partial q_0} < 0$, $\frac{\partial \Pi_M}{\partial q_0} < 0$.

Corollary 1 suggests that raising the quality threshold reduces recycling services, recycling commissions, PI, and the quantity of recycled products, differing from Qin, Chen, Zhang, and Ding [10]. A higher threshold makes recycling less attractive for ECLSC companies as remanufacturing becomes costlier and less profitable. However, an increased threshold does not always lower the manufacturer's valuation of used products. Only when recycling price sensitivity is high and PI costs are low does a higher threshold reduce the value coefficient for used products. Otherwise, manufacturers may increase this coefficient to balance recyclable supply and optimize decisions. Additionally, sales commissions, prices, and overall sales volumes remain unaffected by the quality threshold, despite changes in recycling and remanufacturing. Finally, a higher remanufacturing threshold lowers profits for ECLSC members, making remanufacturing less economically viable. To address this, companies could collaborate with advanced remanufacturers or adopt recycling-friendly product designs [61]. For example, Fairphone, a Netherlands-based smartphone manufacturer, adopts a highly modular product design that facilitates product repair and end-of-life recycling.

Corollary 2. *The impact of the recycling service level sensitivity coefficient ϕ on the optimal decisions and profits is as follows:* $\frac{\partial s^*}{\partial \phi} > 0$, $\frac{\partial \rho_r{}^*}{\partial \phi} > 0$, $\frac{\partial x^*}{\partial \phi} > 0$, $\frac{\partial D_r{}^*}{\partial \phi} > 0$. *When* $\eta > (-1+q_0)^2\phi^2$, *if* $\frac{-2\eta^2}{-4\eta+(-1+q0)^2\phi^2} < H < \frac{2\eta}{3}$, *then* $\frac{\partial \theta^{N^*}}{\partial \phi} > 0$, *otherwise* $\frac{\partial \theta^{N^*}}{\partial \phi} < 0$; *if* $\frac{2\eta^2}{(4\eta-\phi^2(-1+q_0)^2)(1+r_b)} < H < \frac{2\eta}{3+3r_b}$, *then* $\frac{\partial \theta^{B^*}}{\partial \phi} > 0$, *otherwise* $\frac{\partial \theta^{B^*}}{\partial \phi} < 0$; *if* $\frac{2\eta^2}{(1+r_f)(4\eta-(-1+q_0)^2\phi^2)\psi} < H < \frac{2\eta}{3\psi(1+r_f)}$, *then* $\frac{\partial \theta^{F^*}}{\partial \phi} > 0$, *otherwise* $\frac{\partial \theta^{F^*}}{\partial \phi} < 0$. *When* $4(-1+q_0)^2\phi^2 < \eta \leq (-1+q_0)^2\phi^2$, *then* $\frac{\partial \theta^*}{\partial \phi} < 0$. $\frac{\partial p_n{}^*}{\partial \phi} = 0$, $\frac{\partial D^*}{\partial \phi} = 0$, $\frac{\partial \rho^*}{\partial \phi} = 0$; $\frac{\partial \Pi_P}{\partial \phi} > 0$, $\frac{\partial \Pi_M}{\partial \phi} > 0$.

Corollary 2 shows that, as consumers value recycling services more, the E-platform invests in better services to boost participation. Despite rising costs, increased recycling commissions and quantities make recycling more profitable. For the manufacturer, higher volumes of used products enhance remanufacturing benefits, encouraging greater PI investment.

Furthermore, when the recycling price sensitivity is high and the PI cost coefficient is low, the manufacturer raises the valuation of used products to attract consumers, increasing the income from PI. Consumers benefit from higher recycling prices and improved services, unlike in the findings of Wang, Yu, Shen, and Jin [14], where both were not achievable simultaneously. In reality, luxury resale platforms like The RealReal and Vestiaire Collective exemplify this by enhancing services (e.g., free authentication, home pick-up) to attract high-end consumers [62]. Conversely, if PI costs are high or recycling price sensitivity is low, the manufacturer will reduce valuations to manage expenses. Moreover, the recycling service sensitivity coefficient mainly affects the ECLSC recycling segment, indicating that a greater consumer emphasis on recycling services enhances ECLSC efficiency, improves remanufacturing profitability, and benefits both the e-commerce platform and the manufacturer.

Finally, through Corollary 1 and Corollary 2, we find that the impacts of the remanufacturing quality threshold and the recycling service coefficient are not influenced by the presence of financial constraints or differences in financing schemes.

Proof of Corollaries A1 and A2: See Appendix A.2.

5.2. Comparison Between BF and FPF Schemes

To ensure that all financing schemes have optimal solutions and to avoid trivial cases, it is assumed that $H > max(\frac{2\eta^2}{(1+r_b)(4\eta-(-1+q_0)^2\phi^2)}, \frac{2\eta^2}{(1+r_f)(4\eta-(-1+q_0)^2\phi^2)\psi})$ in the following subsections. Based on Propositions 2 and 3, we compared two financing schemes and obtained the following conclusions.

5.2.1. The Optimal Decisions

Corollary 3. *In the case of* $r_b \geq r_f$ *or* $r_f > r_b$ *and* $0 < \psi \leq \frac{1+r_b}{1+r_f}$, *there exist* $s^{F^*} > s^{B^*}$, $\rho_r^{F^*} > \rho_r^{B^*}$, $x^{F^*} > x^{B^*}$, $D_r{}^{F^*} > D_r{}^{B^*}$; *if* $\frac{(-1+q_0)^2\phi^2}{4} < \eta < (-1+q_0)^2\phi^2$, *then* $\theta^{B^*} > \theta^{F^*}$, *otherwise,* $\theta^{F^*} > \theta^{B^*}$. *In the case of* $r_f > r_b$, *when* $\frac{1+r_b}{1+r_f} < \psi < 1$ *there exist* $s^{B^*} > s^{F^*}$, $\rho_r^{B^*} > \rho_r^{F^*}$, $x^{B^*} > x^{F^*}$, $D_r{}^{B^*} > D_r{}^{F^*}$; *if* $\frac{(-1+q_0)^2\phi^2}{4} < \eta < (-1+q_0)^2\phi^2$, *then* $\theta^{F^*} > \theta^{B^*}$, *otherwise,* $\theta^{B^*} > \theta^{F^*}$.

According to Corollary 3, when the bank interest rate is greater than or equal to the FPF interest rate, or when the FPF interest rate is higher and the DF ratio is less than or equal to the threshold, the FPF results in higher recycling service levels, recycling commissions, and a greater manufacturer investment in PI. However, for the valuation of used products, when the recycling price sensitivity coefficient is low, the manufacturer under the BF tends

to set higher valuations to attract consumers and mitigate the higher financing costs of PI capital. Nevertheless, the quantity of used products under the FPF remains higher than that under the BF scheme. When the FPF interest rate is higher and the DF ratio exceeds the threshold, the comparison results are opposite to the above findings. In this scenario, the manufacturer is more motivated to implement recycling, remanufacturing, and PI under the BF. At the same time, the E-platform is more inclined to provide higher levels of recycling services.

A representative real-world example is Tesla, which obtained approximately USD 465 million in favorable financing around 2010 to support manufacturing expansion and technological investment. The reduced capital pressure enabled a substantial investment in production technologies, highlighting the positive role of appropriate financing conditions in promoting manufacturers' technological upgrading [63].

Corollary 4. $\rho^{B^*} = \rho^{F^*}$, $p_n^{B^*} = p_n^{F^*}$, $D^{B^*} = D^{F^*}$.

As shown in Corollary 4, different PI capital financing schemes in this study do not affect the forward logistics channels. Similarly to the results of Chai, Qian, Wang, and Zhu [34], the total product sales remain unchanged, allowing us to better investigate the impact of financing schemes on remanufacturing performance and recycling efficiency.

5.2.2. The Profit Performance

To facilitate a comparison of the profits of ECLSCs, in Corollary 5, we assume $r_b = r_f = 0.0435$, ϕ =1, η =2, H =1.5, and $0 < \beta \leq 1$ ([14,55]). Considering corporate control in EF under the FPF, we assume that $\frac{1}{2} < \psi < 1$.

Corollary 5. *If* $0 < c_n < \hat{c_n}$, *then* ${\Pi_T}^{B^*} > {\Pi_T}^{F^*}$, *otherwise,* ${\Pi_T}^{B^*} < {\Pi_T}^{F^*}$. *The* $\hat{c_n}$ *is positively correlated with* q_0, *where* $\hat{c_n}$ *is placed inAppendix A.3.*

According to Corollary 5, when the unit manufacturing cost exceeds a certain threshold ($\hat{c_n}$), meaning that the cost of producing products using entirely new components is relatively high, the profit of the ECLSC is higher under the FPF. This finding is consistent with Sun, and Chen [64], who show that production cost is one of the key factors influencing firms' financing channel choices. This may be because higher unit manufacturing costs indicate that the manufacturer relies more heavily on remanufactured products and must invest significantly in PI. Since PI often requires substantial financial resources, the FPF, which provides a flexible combination of DF and EF, becomes more advantageous. For instance, companies like Apple Inc and Tesla, which invest in advanced manufacturing technologies and rely on continuous innovation, might find the FPF beneficial as it offers flexible financing options to support innovation. In contrast, when the unit manufacturing cost is below this threshold ($\hat{c_n}$), BF yields a higher profit. In this scenario, the lower reliance on remanufacturing and PI makes traditional BF more suitable. Companies in the fast-moving consumer goods sector may find bank financing (BF) more advantageous for maintaining profitability without the need for extensive innovation financing. TerraCycle specializes in the collection, reuse, and recycling of consumer packaging through standardized circular processes, where remanufacturing costs are relatively low, making traditional bank financing a suitable option.

Furthermore, the remanufacturing quality threshold positively influences the unit manufacturing cost threshold, indicating that, as the remanufacturing quality threshold increases, the cost threshold at which the FPF becomes more advantageous also rises. In practice, when higher standards are set for the quality of used products, such as in the luxury goods industry where strict conditions are required for recycled items, the benefits

of the FPF may diminish. Thus, ECLSC companies might need to weigh the potential benefits of FPF against the increasing quality threshold to determine the most effective financing strategy.

5.2.3. Environmental Performance

Although financial returns remain a critical measure of success in the private sector, core companies like Walmart and Carrefour prioritize building green supply chains by setting environmental standards for their suppliers, who risk losing their contracts if they fail to meet these criteria [65]. Therefore, it is essential to analyze the environmental impact (EI) under different schemes. We use the EI index to compare the environmental effects under different financing schemes [32,66–68]. We define the EI index function as $\chi(D - D_r)+\kappa D_r$, where χ and κ denote the environmental impact of each brand-new/remanufactured product over its lifecycle, respectively. This linear specification provides a parsimonious proxy for aggregating EI and is consistent with studies that approximate environmental damage using total material or energy usage. However, it should be noted that the potential environmental effects of PI, as well as the impacts arising from recycling logistics, are not directly captured by the EI function. Nevertheless, the assumption that remanufactured products generate a lower environmental impact than newly manufactured products is widely supported in the existing literature. For example, Esenduran, et al. [69] show that remanufacturing consumes 20–60% less energy than producing new products. For simplicity, we normalize χ to 1, while κ is set to 0.5. By substituting equilibrium results, the following outcomes and Corollaries are derived.

$$EI^B = \frac{1}{4}\left(\alpha - \beta c_n - \frac{2H\eta^2 c_n(1+r_b)}{-2\eta^2+H\left(4\eta-\phi^2(-1+q_0)^2\right)(1+r_b)}\right) \tag{7}$$

$$EI^F = \frac{1}{4}\left(\alpha - \beta c_n - \frac{2H\eta^2\psi c_n\left(1+r_f\right)}{-2\eta^2+H\psi\left(4\eta-\phi^2(-1+q_0)^2\right)\left(1+r_f\right)}\right) \tag{8}$$

Corollary 6. *If $r_b \geq r_f$ or $r_f > r_b$ and $0< \psi \leq \psi_1$, then $EI^B > EI^F$; if $r_f > r_b$ and $\psi_1< \psi \leq 1$, then, $EI^F > EI^B$, where $\psi_1 = \frac{1+r_b}{1+r_f}$.*

Corollary 6 indicates that, when the BF interest rate is greater than or equal to the FPF interest rate, or when the FPF interest rate is higher and the DF ratio is less than or equal to the threshold, the EI under the BF is higher than that under the FPF. Combined with Corollary 3, this outcome suggests that the lower recycling efficiency of the ECLSC under the BF forces manufacturers to rely more heavily on new components in production, leading to significantly increased environmental damage.

Substituting the parameter values from Corollary 5 (i.e., $r_b = r_f = 0.0435$, ϕ =1, η =2, H =1.5, $0< \beta \leq 1$, $\frac{1}{2}< \psi <1$), we observe that the EI under the FPF scheme is consistently lower than that under the BF scheme. Specifically, when $\hat{c_n} < c_n < \frac{\alpha}{\beta}$, opting for the FPF scheme enables the simultaneous achievement of maximum economic benefits and minimized environmental damage for the ECLSC. Aligning financing decisions with sustainability objectives through such strategies can enhance overall performance. Furthermore, this finding suggests that socially responsible manufacturing companies operating under the BF scheme must place a greater emphasis on investing in carbon reduction, green innovation, and other sustainable practices to reduce their EI effectively.

Proof of Corollaries A3–A6: See Appendix A.3.

6. Numerical Analysis

This section utilizes numerical examples to further analyze the profit comparison of the profits of ECLSCs. The numerical examples are sourced from Wang, Yu, Shen, and Jin [14], with certain values adjusted to align with the conditions of this study's model. We set the bank interest rate $r_b = 0.0435$, in line with the benchmark annual interest rate for short-term loans in China. The remaining settings are as follows: the market size α =50 and the sales price sensitivity coefficient β =1.

6.1. The Combined Impact of Unit Cost of Manufacturing and Quality Threshold

Building on and refining the parameter settings in Yang, Tang, and Zhang [35], Reza-Gharehbagh, Arisian, Hafezalkotob, and Makui [47], and Sun, and Chen [64], we assume that η =2, ϕ =1, ψ =0.95, and H =1.5. By setting $c_n \in [2, 7]$ and $q_0 \in [0.1, 0.8]$, we use three sets of parameters to plot the changes in the profit of the ECLSC with the unit cost of manufacturing c_n and the quality threshold q_0 in Figure 4.

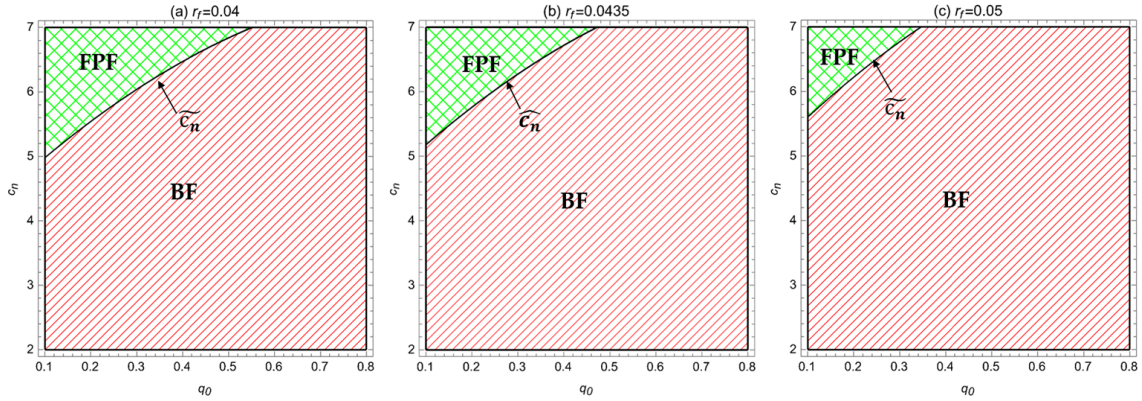


Figure 4. Impact of c_n and q_0 on Π_T.

Figure 4 illustrates that, when c_n is relatively high and q_0 is relatively low, which are conditions favorable for remanufacturing, choosing the FPF results in a higher overall profit for the ECLSC. As q_0 increases, the threshold also increases, which is consistent with the result in Corollary 5. Moreover, it is noteworthy that the relationship between the interest rates of the two financing schemes does not affect the choice of the optimal financing scheme currently. Furthermore, as shown in Figure 5, FPF consistently exhibits a lower EI within this range. When combined with the results in Figure 4, this suggests that choosing FPF may represent a viable option for balancing EI and economic performance.

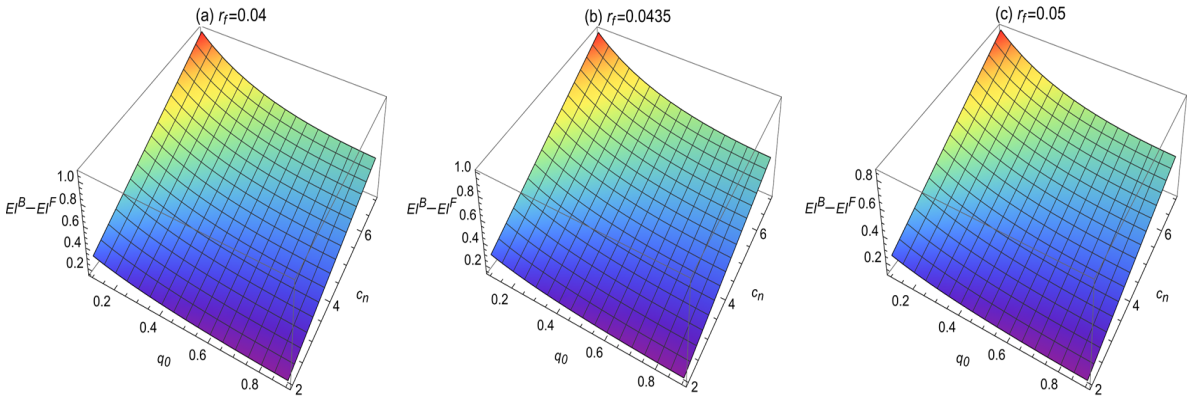


Figure 5. Impact of c_n and q_0 on $EI^B - EI^F$.

6.2. The Combined Impact of FinTech Platform Interest Rate and Debt Financing Ratio

Assuming that $\eta = 2$, $\phi = 1$, and $H = 1.5$ [35], and after we set $r_f \in [0.04, 0.05]$ and $\psi \in [0.95, 1]$, the combined impact of r_f and ψ is illustrated in Figure 6. Figure 6 shows that, when r_f is relatively low and ψ is relatively high, the ECLSC profit is greater under the FPF. Combined with Corollary 3, this indicates that the FPF achieves higher recycling efficiency and PI levels in this situation. Otherwise, the BF becomes the preferable choice. Figure 7 shows that, when both r_f and ψ are relatively high, BF results in a lower EI, which is consistent with Corollary 6.

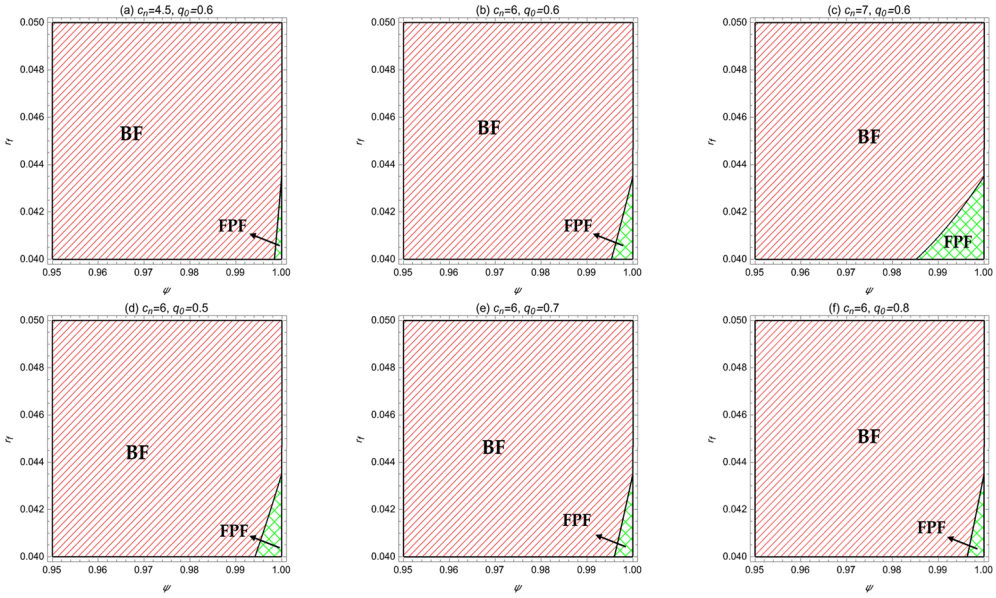


Figure 6. Impact of r_f and ψ on Π_T.

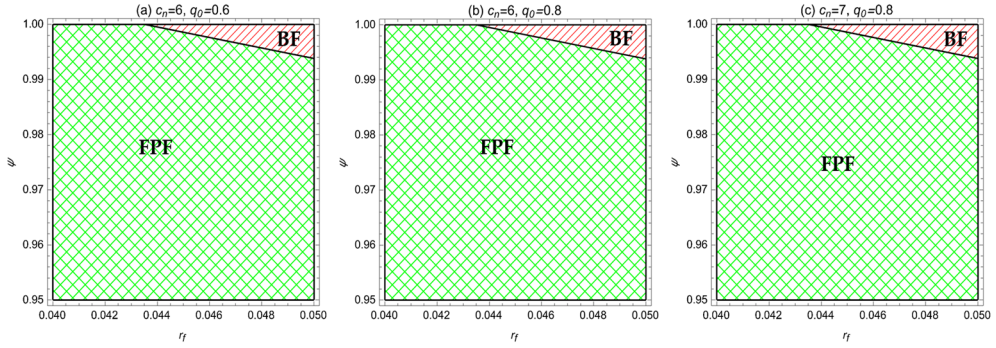


Figure 7. Impact of r_f and ψ on EI.

6.3. The Impact of Relevant Parameters

This section explores how key parameters such as the PI cost coefficient H, the recycling price sensitivity coefficient η, and the recycling service sensitivity coefficient ϕ influence the ECLSC profit. Referring to and extending the parameter settings in Yang, Tang, and Zhang [35] and Wang, Yu, Shen, and Jin [14], the specific parameter settings are detailed in Table 4.

Table 4. Parameter settings.

Parameter	Range	Other Parameters						
		α	β	c_n	q_0	r_b	η	ϕ
H	$[1.2, 2]$	50	1	6	0.5	0.0435	2	1
Parameter	Range	Other Parameters						
		α	β	c_n	q_0	r_b	H	ϕ
η	$[0.5, 2.5]$	50	1	6	0.5	0.0435	1.5	1
Parameter	Range	Other Parameters						
		α	β	c_n	q_0	r_b	η	H
ϕ	$(0, 2]$	50	1	6	0.5	0.0435	2	1.5

Figure 8 illustrates the impact of H on the difference in profits of ECLSCs between the two financing schemes. As shown in Figure 8, when H is low, the profit under the BF scheme is lower than under the FPF. However, as H increases, the profit under BF surpasses that of the FPF. Combining these findings with those from Section 6.1, we conclude that, in scenarios favorable to remanufacturing, the ECLSC can achieve higher profits under the FPF. These results suggest that the ECLSC company needs to carefully evaluate its PI costs and ensure a strategic alignment with industry conditions before selecting a financing option. Figures 9 and 10 show that, when η or ϕ is low, the ECLSC profit is greater under BF. When η or ϕ is high, the FPF results in a higher profit.

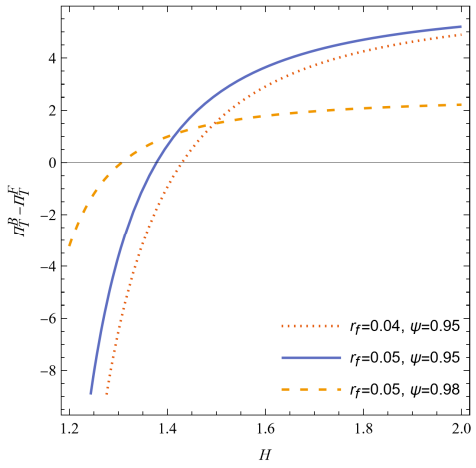


Figure 8. Impact of H on $\Pi_T^B - \Pi_T^F$.

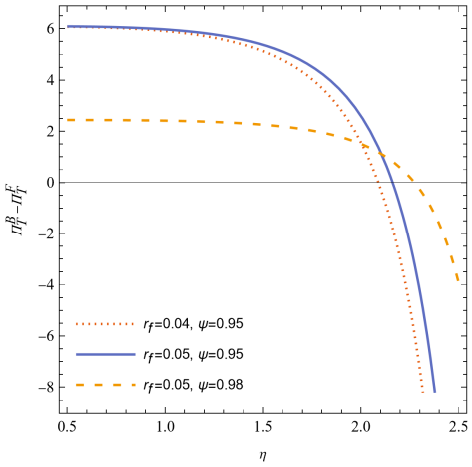


Figure 9. Impact of η on $\Pi_T^B - \Pi_T^F$.

Overall, understanding and anticipating market condition changes related to recycling price and service sensitivity can lead to more informed and effective financing decisions, ultimately enhancing the sustainability and profitability of the ECLSC.

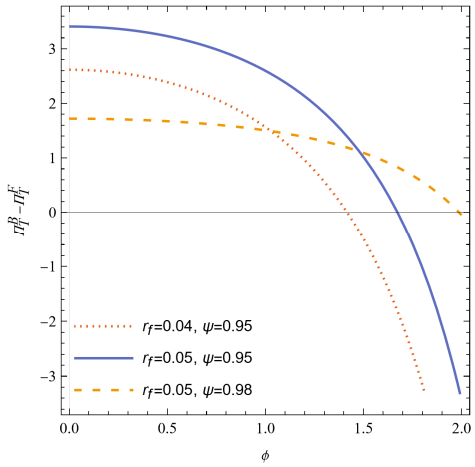


Figure 10. Impact of ϕ on $\Pi_T^B - \Pi_T^F$.

6.4. Sensitivity Analysis

In this subsection, we conduct sensitivity analyses to examine the robustness of our analytical results. The corresponding results are summarized in Tables 5 and 6.

Table 5. The sensitivity analysis results for BF model ($r_b = 0.0435$).

q_0	ϕ	H	η	s	ρ_r	ρ	x	p_n	θ	Π_P	Π_M
0.25	1	1.15	2	3.89	1.73	24	8.65	38	7.96	298.38	152.97
0.35	1	1.15	2	2.85	1.46	24	7.32	38	7.89	296.78	150.43
0.5	1	1.15	2	1.84	1.23	24	6.15	38	8.61	295.38	148.54
0.25	1	1.5	2	1.30	1.24	24	2.20	38	2.64	291.44	146.14
0.35	1	1.5	2	1.05	1.17	24	2.07	38	2.92	291.24	145.90
0.5	1	1.5	2	0.76	1.09	24	1.94	38	3.54	291.03	145.66
0.25	1	1.15	1	0.85	1.32	24	0.94	38	1.05	289.13	144.74
0.35	1	1.15	1	0.68	1.22	24	0.87	38	1.38	289.05	144.64
0.5	1	1.15	1	0.48	1.12	24	0.80	38	1.91	288.96	144.54
0.5	0.6	1.15	2	0.97	1.07	24	5.36	38	8.19	294.43	147.45
0.5	0.8	1.15	2	1.36	1.14	24	5.68	38	8.36	294.81	147.87
0.5	1.2	1.15	2	2.47	1.37	24	6.85	38	8.99	296.22	149.63
0.5	0.6	1.5	2	0.43	1.03	24	1.82	38	3.64	290.86	145.48
0.5	0.8	1.5	2	0.59	1.06	24	1.87	38	3.60	290.93	145.55
0.5	1.2	1.5	2	0.95	1.14	24	2.02	38	3.46	291.16	145.81
0.5	0.6	1.15	1	0.27	1.04	24	0.74	38	2.16	288.89	144.46
0.5	0.8	1.15	1	0.37	1.07	24	0.77	38	2.06	288.92	144.49
0.5	1.2	1.15	1	0.61	1.18	24	0.84	38	1.73	289.01	144.60

Table 6. The sensitivity analysis results for FPF model ($r_f = 0.0435$, $\psi = 0.98$).

q_0	ϕ	H	η	s	ρ_r	ρ	x	p_n	θ	Π_P	Π_M
0.3	1	1.15	2	3.96	1.69	24	9.62	38	9.38	299.31	150.50
0.35	1	1.15	2	3.36	1.55	24	8.78	38	9.28	298.32	148.94
0.5	1	1.15	2	2.11	1.26	24	7.18	38	9.85	296.44	146.35
0.3	1	1.5	2	1.22	1.21	24	2.27	38	2.89	291.49	143.19
0.35	1	1.5	2	1.10	1.18	24	2.21	38	3.04	291.39	143.08

Table 6. *Cont.*

q_0	ϕ	H	η	s	ρ_r	ρ	x	p_n	θ	Π_P	Π_M
0.5	1	1.5	2	0.79	1.10	24	2.06	38	3.68	291.16	142.82
0.3	1	1.15	1	0.77	1.27	24	0.94	38	1.24	289.11	141.81
0.35	1	1.15	1	0.69	1.23	24	0.91	38	1.40	289.06	141.76
0.5	1	1.15	1	0.49	1.12	24	0.83	38	1.95	288.98	141.66
0.5	0.6	1.15	2	1.08	1.08	24	6.14	38	9.20	295.22	144.95
0.5	0.8	1.15	2	1.54	1.15	24	6.56	38	9.46	295.71	145.48
0.5	1.2	1.15	2	2.87	1.43	24	8.12	38	10.44	297.55	147.81
0.5	0.6	1.5	2	0.45	1.03	24	1.94	38	3.78	290.97	142.62
0.5	0.8	1.5	2	0.61	1.06	24	1.99	38	3.74	291.05	142.71
0.5	1.2	1.5	2	0.99	1.15	24	2.15	38	3.61	291.30	142.98
0.5	0.6	1.15	1	0.27	1.04	24	0.77	38	2.20	288.91	141.58
0.5	0.8	1.15	1	0.37	1.07	24	0.79	38	2.09	288.94	141.61
0.5	1.2	1.15	1	0.62	1.19	24	0.88	38	1.76	289.03	141.72

As shown in these tables, the quality threshold has a negative impact on the recycling service level, recycling commission, PI level, and profits, whereas the recycling service level sensitivity exerts a positive effect on these variables. In contrast, neither the sales price nor the sales commission is affected. Moreover, their impacts on the value coefficient of used products depend on the PI cost coefficient and the recycling price sensitivity coefficient. These analytical results are consistent with Corollaries 1 and 2.

7. Model Extension: Decision Making with Fairness Concern

In practice, stakeholders may act against their own interests to address perceived unfairness and seek more equitable outcomes [70]. Manufacturers often face profit gaps due to the economies of scale of E-platforms, raising concerns about fair profit distribution [6]. Therefore, this section incorporates the fairness concern (FC) behavior of the manufacturer into decision-making. According to Wang, Wang, Cheng, Zhou, and Gao [6], the utility function of the manufacturer with FCs is defined as follows.

$$U_M = \Pi_M - \mu(\Psi\Pi_P - \Pi_M) \tag{9}$$

We focus on a single manufacturer to clearly capture the core interaction with the E-platform, even though most platforms engage with multiple manufacturers in practice. Therefore, directly comparing the income gap between the two parties in this section is inappropriate. It is necessary to introduce a relative fairness reference point, represented by Ψ ($\Psi > 0$). In Equation (9), μ ($0 < \mu \leq 1$) denotes the manufacturer's FC coefficient, reflecting the decrease in the manufacturer's utility when its profit is less than $\Psi\Pi_P$.

In this scenario, the manufacturer makes decisions based on utility maximization, while the E-platform continues to focus on profit maximization. The optimal outcomes and the conditions that need to be satisfied are summarized in Table 7.

From Table 7, it is evident that, when $\mu = 0$, the optimal solutions of the models with FC are consistent with those of the models without FC. Regardless of the financing scheme, the FC coefficient consistently affects the optimal solutions and profits in the same direction.

Corollary 7. *The impact of the FC coefficient μ on optimal decisions is as follows:* $\frac{\partial s^*}{\partial \mu} < 0$, $\frac{\partial \rho_r{}^*}{\partial \mu} < 0$, $\frac{\partial x^*}{\partial \mu} < 0$, $\frac{\partial D_r{}^*}{\partial \mu} < 0$; *if* $\eta > \frac{(-1+q0)^2(1+\mu)\phi^2}{1+\mu+\mu\Psi}$, *then* $\frac{\partial \theta^{N-FC^*}}{\partial \mu} > 0$, *otherwise* $\frac{\partial \theta^{N-FC^*}}{\partial \mu} < 0$; *if* $\eta > \frac{(1+\mu)\phi^2(-1+q_0)^2}{1+\mu+\mu\Psi}$ *and* $\frac{2\eta^2(1+\mu+\mu\Psi)}{(4\eta(1+\mu+\mu\Psi)-(1+\mu)\phi^2(-1+q_0)^2)(1+r_b)} < H < \frac{2\eta}{3+3r_b}$, *then* $\frac{\partial \theta^{B-FC^*}}{\partial \mu} < 0$,

otherwise $\frac{\partial\theta^{B-FC^*}}{\partial\mu} > 0$; *if* $\eta > \frac{(-1+q_0)^2(1+\mu)\phi^2\psi}{\psi+\mu\psi+\mu\Psi}$ *and* $\frac{2\eta^2(\psi+\mu\psi+\mu\Psi)}{(1+r_f)\psi((1+\mu)(4\eta-(-1+q_0)^2\phi^2)\psi+4\eta\mu\Psi)} < H < \frac{2\eta}{3\psi+3r_f\psi}$, *then* $\frac{\partial\theta^{F-FC^*}}{\partial\mu} < 0$, *otherwise* $\frac{\partial\theta^{F-FC^*}}{\partial\mu} > 0$. $\frac{\partial {p_n}^*}{\partial\mu} = 0$, $\frac{\partial D^*}{\partial\mu} = 0$, $\frac{\partial\rho^*}{\partial\mu} = 0$.

Table 7. Optimal solutions of models with FC.

Variables	Solutions
(a) NC with FC ($\eta > \frac{(1+\mu)\phi^2(-1+q_0)^2}{4(1+\mu+\mu\Psi)}$, $H > -\frac{2\eta^2(1+\mu+\mu\Psi)}{-4\eta(1+\mu+\mu\Psi)+(1+\mu)\phi^2(-1+q_0)^2}$)	
s^{N-FC^*}	$\frac{H\eta(1+\mu)\phi c_n(-1+q_0)}{-4H\eta(1+\mu+\mu\Psi)+2\eta^2(1+\mu+\mu\Psi)+H(1+\mu)\phi^2(-1+q_0)^2}$
$\rho_r^{N-FC^*}$	$\frac{\eta(-2H+\eta)(1+\mu)c_n}{-4H\eta(1+\mu+\mu\Psi)+2\eta^2(1+\mu+\mu\Psi)+H(1+\mu)\phi^2(-1+q_0)^2}$
ρ^{N-FC^*}	$\frac{(1+\mu)(\alpha-\beta c_n)}{2\beta(1+\mu+\mu\Psi)}$
$p_n^{N-FC^*}$	$\frac{1}{4}\left(\frac{3\alpha}{\beta}+c_n\right)$
θ^{N-FC^*}	$\frac{2Hc_n(\eta\mu\Psi+(1+\mu)(\eta-\phi^2(-1+q_0)^2))}{(2\eta(-2H+\eta)\mu\Psi+(1+\mu)(2\eta(-2H+\eta)+H\phi^2(-1+q_0)^2))(-1+q_0^2)}$
x^{N-FC^*}	$\frac{-\eta^2(1+\mu+\mu\Psi)c_n}{-4H\eta(1+\mu+\mu\Psi)+2\eta^2(1+\mu+\mu\Psi)+H(1+\mu)\phi^2(-1+q_0)^2}$
(b) BF with FC ($\eta > \frac{(1+\mu)\phi^2(-1+q_0)^2}{4(1+\mu+\mu\Psi)}$, $H > \frac{2\eta^2(1+\mu+\mu\Psi)}{(4\eta(1+\mu+\mu\Psi)-(1+\mu)\phi^2(-1+q_0)^2)(1+r_b)}$)	
s^{B-FC^*}	$\frac{H\eta(1+\mu)\phi c_n(-1+q_0)(1+r_b)}{2\eta^2(1+\mu+\mu\Psi)+H(-4\eta(1+\mu+\mu\Psi)+(1+\mu)\phi^2(-1+q_0)^2)(1+r_b)}$
$\rho_r^{B-FC^*}$	$\frac{\eta(1+\mu)c_n(-\eta+2H(1+r_b))}{-2\eta^2(1+\mu+\mu\Psi)+H(4\eta(1+\mu+\mu\Psi)-(1+\mu)\phi^2(-1+q_0)^2)(1+r_b)}$
ρ^{B-FC^*}	$\frac{(1+\mu)(\alpha-\beta c_n)}{2\beta(1+\mu+\mu\Psi)}$
$p_n^{B-FC^*}$	$\frac{1}{4}\left(\frac{3\alpha}{\beta}+c_n\right)$
θ^{B-FC^*}	$\frac{2Hc_n(\eta(1+\mu+\mu\Psi)-(1+\mu)\phi^2(-1+q_0)^2)(1+r_b)}{(-1+q_0^2)(2\eta^2(1+\mu+\mu\Psi)+H(-4\eta(1+\mu+\mu\Psi)+(1+\mu)\phi^2(-1+q_0)^2)(1+r_b))}$
x^{B-FC^*}	$\frac{-\eta^2(1+\mu+\mu\Psi)c_n}{2\eta^2(1+\mu+\mu\Psi)+H(-4\eta(1+\mu+\mu\Psi)+(1+\mu)\phi^2(-1+q_0)^2)(1+r_b)}$
(c) FPF with FC ($\eta > \frac{(1+\mu)\phi^2(-1+q_0)^2}{4(1+\mu+\mu\Psi)}$, $H > \frac{2\eta^2(\psi+\mu\psi+\mu\Psi)}{\psi(4\eta\mu\Psi+(1+\mu)\psi(4\eta-\phi^2(-1+q_0)^2))(1+r_f)}$)	
s^{F-FC^*}	$\frac{H(1+\mu)\phi\psi^2c_n(-1+q_0)(1+r_f)}{2(\psi+\mu\psi+\mu\Psi)(\eta-2H\psi(1+r_f))(-1-\frac{H(1+\mu)\phi^2\psi^2(-1+q_0)^2(1+r_f)}{2\eta(\psi+\mu\psi+\mu\Psi)(\eta-2H\psi(1+r_f))})}$
$\rho_r^{F-FC^*}$	$\frac{\eta(1+\mu)\psi c_n(-\eta+2H\psi(1+r_f))}{-2\eta^2(\psi+\mu\psi+\mu\Psi)+4H\eta\psi(\psi+\mu\psi+\mu\Psi)\left(1+r_f\right)-H(1+\mu)\phi^2\psi^2(-1+q_0)^2(1+r_f)}$
ρ^{F-FC^*}	$\frac{(1+\mu)\psi(\alpha-\beta c_n)}{2\beta(\psi+\mu\psi+\mu\Psi)}$
$p_n^{F-FC^*}$	$\frac{1}{4}\left(\frac{3\alpha}{\beta}+c_n\right)$
θ^{F-FC^*}	$\frac{2H\psi c_n(\eta(\psi+\mu\psi+\mu\Psi)-(1+\mu)\phi^2\psi(-1+q_0)^2)(1+r_f)}{(-1+q_0^2)(2\eta^2(\psi+\mu\psi+\mu\Psi)-4H\eta\psi(\psi+\mu\psi+\mu\Psi)(1+r_f)+H(1+\mu)\phi^2\psi^2(-1+q_0)^2(1+r_f))}$
x^{F-FC^*}	$\frac{-\eta^2(\psi+\mu\psi+\mu\Psi)c_n}{2\eta^2(\psi+\mu\psi+\mu\Psi)-4H\eta\psi(\psi+\mu\psi+\mu\Psi)\left(1+r_f\right)+H(1+\mu)\phi^2\psi^2(-1+q_0)^2(1+r_f)}$

Corollary 7 reveals that, when manufacturers are concerned about fairness, an increase in the FC coefficient leads the E-platform to reduce the recycling service level, recycling commission, and sales commission in an attempt to mitigate the impact of the manufacturer's FC. Simultaneously, the manufacturer's focus on fairness weakens its incentive to invest in PI. It is worth noting that the impact of the FC coefficient on the valuation of used products depends on specific conditions involving the recycling price sensitivity coefficient and the PI cost coefficient. Under certain conditions, an increase in fairness concerns might unexpectedly lead to higher product valuations, reflecting the manufacturer's flexible pricing strategy aimed at reducing the profit gap. It is also observed that this range differs between the capital-unconstrained and financing models. These changes consequently have a negative impact on the recycling efficiency of the ECLSC.

Corollary 8. *The impact of the FC coefficient μ on profits is as follows: $\frac{\partial \Pi_P}{\partial \mu} < 0$; the impact of μ on ${\Pi_M}^*$ is not linear, e.g., if $\eta > \frac{\phi^2(2+\mu(2+3\Psi))(-1+q_0)^2}{4(1+\mu+\mu\Psi)}$ and $H \geq -\frac{2\eta^2(1+\mu+\mu\Psi)}{-4\eta(1+\mu+\mu\Psi)+\phi^2(2+\mu(2+3\Psi))(-1+q_0)^2}$, then $\frac{\partial {\Pi_M}^{N-FC^*}}{\partial \mu} > 0$; if $\eta > \frac{(-1+q0)^2\phi^2(2+\mu(2+3\Psi))}{4(1+\mu+\mu\Psi)}$ and $H \geq \frac{2\eta^2(1+\mu+\mu\Psi)}{(1+i)(4\eta(1+\mu+\mu\Psi)-(-1+q0)^2\phi^2(2+\mu(2+3\Psi)))}$, then $\frac{\partial {\Pi_M}^{B-FC^*}}{\partial \mu} > 0$; if $\eta > \frac{(-1+q_0)^2\phi^2(2(1+\mu)\psi+3\mu\Psi)}{4(\psi+\mu\psi+\mu\Psi)}$ and $H \geq \frac{2\eta^2(\psi+\mu\psi+\mu\Psi)}{(1+r_f)\psi(4\eta(\psi+\mu\psi+\mu\Psi)-(-1+q_0)^2\phi^2(2(1+\mu)\psi+3\mu\Psi))}$, then $\frac{\partial {\Pi_M}^{F-FC^*}}{\partial \mu} > 0$.*

Corollary 8 shows that the manufacturer's focus on the profit gap results in a decrease in the E-platform's profit, but the effect on the manufacturer's profit is complex and non-linear. While FCs are generally perceived as detrimental to efficiency and economic profit [6,15], within a certain range, they can encourage the manufacturer to adjust its decisions, potentially increasing the manufacturer's profit. Rather than passively accepting platform-defined arrangements, Haier collaborated with Alibaba to make use of the platform's data and information capabilities, which supported coordination in service and logistics operations (https://www.haier.com/global/press-events/news/20131209_142730.shtml) (accessed on 23 December 2025).

Due to the complicated profit results, we compare the ECLSC profit by applying the numerical values from Corollary 5 that also satisfy the optimal solution conditions under models with FCs and referencing Wang, Wang, Cheng, Zhou, and Gao [6] and Qin, et al. [71], assuming μ =0.1, Ψ =2, and $r_b = r_f = 0.05$.

Corollary 9. *If the unit manufacturing cost satisfies $C(c_n) < 0$, then ${\Pi_T}^{B-FC^*} > {\Pi_T}^{F-FC^*}$, otherwise ${\Pi_T}^{F-FC^*} > {\Pi_T}^{B-FC^*}$. Among them, $C(c_n)$ can be found in Appendix A.4.*

According to Corollary 9, when the manufacturer exhibits FC behavior, the ECLSC profit under different financing schemes, similar to the results of Corollary 5, is influenced by the unit manufacturing cost. When the unit manufacturing cost falls within a certain range, the ECLSC profit under the BF is higher than that under the FPF, as illustrated in Figure 11 (the parameters follow those used in Section 6). Combining Figure 12, FPF is more likely to serve as an option for balancing environmental performance and economic profit, suggesting a conclusion consistent with the scenario in which FC is not considered.

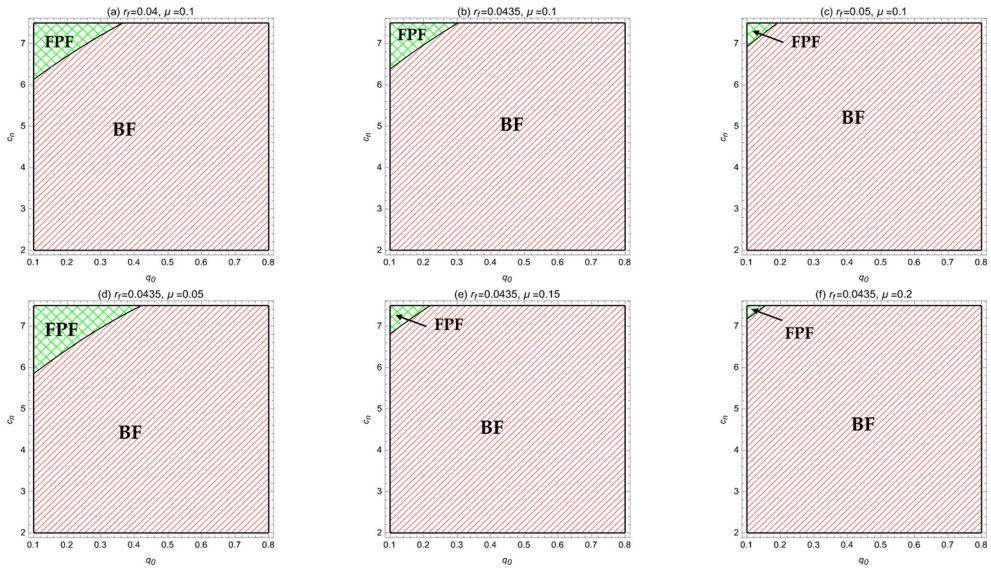


Figure 11. Impact of c_n and q_0 on Π_T with FC.

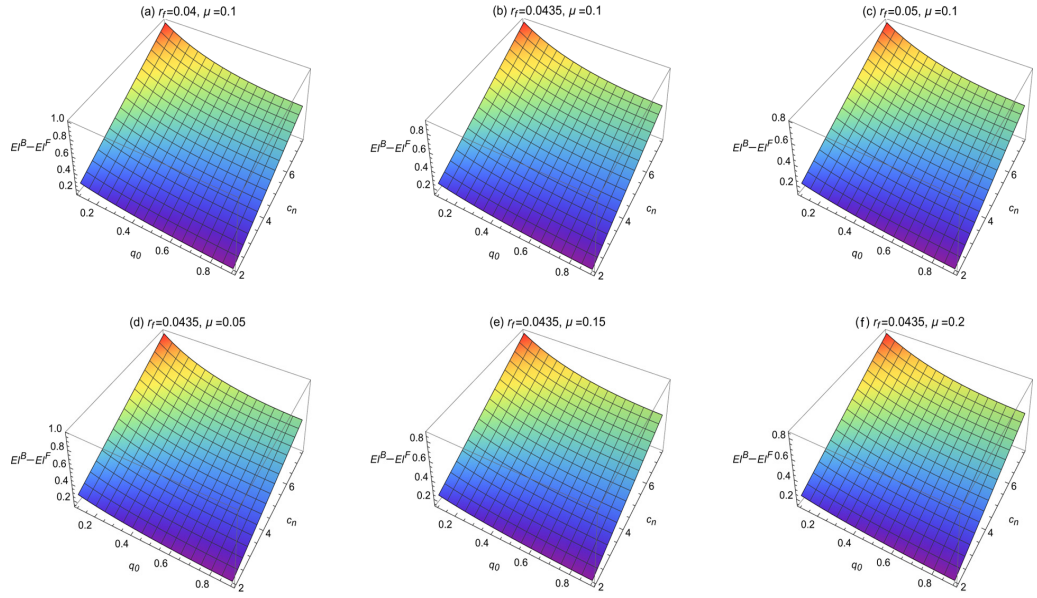


Figure 12. Impact of c_n and q_0 on $EI^B - EI^F$ with FC.

Proof of Corollaries A7–A9: See Appendix A.4.

8. Conclusions and Management Implications

This study constructs an ECLSC with an E-platform and a capital-constrained manufacturer, considering uncertainties in used product quality, PI, and FC. It examines optimal decisions under different financing schemes, analyzes the effects of remanufacturing quality thresholds and recycling service sensitivity on decisions and profits, and identifies the best financing scheme through comparative and numerical analyses. Additionally, it compares EI as a CE performance metric and explores the impact of the manufacturer's FC on decisions and financing strategies. Based on both analytical and numerical studies, we derived the following major findings and their respective implications.

First, for capital-constrained ECLSCs, the financing scheme selection depends on various factors, which extends the findings of [47].

1. The FPF scheme is ideal when the unit remanufacturing cost exceeds the threshold, which correlates positively with the remanufacturing quality threshold. Therefore, it is recommended that enterprises establish cooperative mechanisms with FinTech platforms and integrate them with their ERP and inventory management systems to provide real-time insights into various operational data, facilitate accurate cost tracking, and jointly develop appropriate financing strategies. FPF is also preferable when PI cost is low, making it suitable for industries like fast-moving consumer goods and the luxury industry, where manufacturing is mature and profitable.
2. Attention should be given to the financing interest rate and DF ratio. When the FPF interest rate is relatively low and the DF ratio is relatively high, the FPF becomes the preferred option due to its ability to achieve higher recycling efficiency and improved PI levels within the ECLSC. Thus, FinTech platforms might consider setting more competitive interest rates and balancing the proportions of DF and EF. This approach could help ensure that their financing offerings continue to appeal to companies seeking to optimize their ECLSC operations.
3. A low consumer sensitivity to recycling prices or service favors BF. The growing importance of consumers in the e-commerce economy is undeniable. JD.com, a leading Chinese e-commerce company, utilizes cloud computing and big data to analyze consumer behavior and preferences, enriching user profiles and supporting its financial services. In addition, E-platforms can consider leveraging blockchain technology to build a reliable transaction record system, enhance the transparency of supply chain information, and help manufacturers have a greater chance of obtaining financing at a low cost, reducing their reliance on single-channel financing.

Second, BF increases environmental impact, especially when its interest rate is comparable to or higher than the FPF rate or when the FPF rate is higher but the DF ratio is low. This is due to the lower recycling efficiency, requiring more new components. In contrast, the FPF scheme consistently reduces environmental impact within a specific range, balancing economic gains with environmental benefits. Manufacturers using the BF scheme should focus on carbon reduction, green innovation, and sustainable practices to minimize their environmental footprint.

Third, a higher remanufacturing quality threshold reduces recycled product volume in the ECLSC, diminishing remanufacturing profitability and overall ECLSC profits. Notably, this threshold only lowers the manufacturer's valuation of used products when the recycling price sensitivity is high and PI cost is low; otherwise, the manufacturer increases the valuation to optimize recycling. To address these challenges, manufacturers can enhance product design and collaborate with advanced remanufacturers. Policymakers can also offer incentives, such as China's subsidies for recycling WEEE and EV batteries, to promote recycling and technological upgrades [72,73].

Moreover, a higher consumer sensitivity to E-platform recycling services positively impacts the ECLSC, benefiting consumers through better services, encouraging manufacturers to recycle and invest in PI, and boosting ECLSC profits. Unlike Wang, Yu, Shen, and Jin [14], who found that improved services could lower recycling prices, this study shows that a high consumer sensitivity to recycling prices combined with a low cost of PI allows consumers to benefit from higher valuations of used products. This highlights the need for E-platforms to enhance consumer sensitivity through marketing, surveys, and promotions.

Finally, manufacturers' FC behavior reduces ECLSC recycling efficiency and E-platform profits, highlighting the need for fair profit-sharing rules and regulatory oversight. Interestingly, within certain ranges of recycling price sensitivity and PI cost, manufacturers' profits may increase with higher FC coefficients. In such cases, the optimal financing scheme remains largely determined by unit manufacturing costs, similar to scenarios without FC.

However, this study has several limitations that future research could address. First, it assumes a linear product demand function, and future work could explore the effects of demand uncertainty on ECLSCs. Second, this study assumes that the E-platform and the manufacturer are all risk-neutral when examining different financing strategies. Therefore, future research could further explore how financing decisions by supply chain members are influenced by different risk preferences. Additionally, scenarios where the financing interest rate is an endogenous variable could be considered, exploring interest rate decisions under different financing strategies. Finally, the model could be extended to more complex scenarios, such as multi-enterprise competition, government intervention, or cases in which the E-platform directly provides financing.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ECLSC	E-commerce closed-loop supply chain (ECLSC)
CLSC	Closed-loop supply chain
PI	Process innovation
BF	Bank financing
FPF	FinTech platform financing
DF	Debt financing
EF	Equity financing
FCs	Fairness concerns

Appendix A

Appendix A.1. Proof of Propositions A1–A3

Proposition A1. *The Hessian matrix of* Π_M^N *with respect to* θ^N, p_n^N, *and* x^N *can be solved as follows:* $M_1 = \begin{bmatrix} -\frac{1}{2}(-1+{q_0}^2)^2\eta & 0 & -\frac{1}{2}(-1+{q_0}^2)\eta \\ 0 & -2\beta & 0 \\ -\frac{1}{2}(-1+q_0)(1+q_0)\eta & 0 & -H \end{bmatrix}$. *When* $H > \frac{\eta}{2}$, M_1 *is a negative definite matrix. Solving the first order condition of* Π_M^N *yields* $\theta^N({\rho_r}^N, s^N) = \frac{2H\eta(-{\rho_r}^N+c_n)+2s^N(H-\eta)\phi(-1+q_0)}{\eta(-2H+\eta)(-1+q_0^2)}$, $x^N({\rho_r}^N, s^N) = \frac{c_n\eta-\eta{\rho_r}^N+s^N\phi(1-q_0)}{2H-\eta}$, $p_n{}^N(\rho^N) = \frac{\alpha+\beta(c_n+\rho^N)}{2\beta}$. *Substituting those into Equation (1), we then obtain the Hessian matrix of* Π_P^N *with respect to* ρ_r^N, ρ^N, *and* s^N, $M_2 = \begin{bmatrix} \frac{2H\eta}{-2H+\eta} & 0 & -\frac{H(-1+q_0)\phi}{2H-\eta} \\ 0 & -\beta & 0 \\ -\frac{H(-1+q_0)\phi}{2H-\eta} & 0 & -1 \end{bmatrix}$. *When* $H > \frac{2\eta^2}{-4\eta+(-1+q_0)^2\phi^2}$ *and*

$\eta > \frac{(-1+q_0)^2\phi^2}{4}$, M_2 *is a negative definite matrix. Solving the first order condition of Equation (1) yields* s^{N*}, ρ^{N*}, *and* ρ_r^{N*}. *Substituting these solutions into* $\theta^N(\rho_r{}^N, s^N)$, $x^N(\rho_r{}^N, s^N)$, *and* $p_n{}^N(\rho^N)$ *derives* p_n^{N*}, θ^{N*}, *and* x^{N*}.

Proposition A2. *The Hessian matrix of* Π_M^B *with respect to* θ^B, p_n^B, *and* x^B *can be solved as follows:* $M_3 = \begin{bmatrix} -\frac{1}{2}(-1+q_0{}^2)^2\eta & 0 & -\frac{1}{2}(-1+q_0{}^2)\eta \\ 0 & -2\beta & 0 \\ -\frac{1}{2}(-1+q_0)(1+q_0)\eta & 0 & -H(1+r_b) \end{bmatrix}$. *When* $H > \frac{\eta}{2}(1+r_b)$, M_3 *is a negative definite matrix. Solving the first order condition of* Π_M^B *yields* $\theta^B(\rho_r{}^B, s^B) = \frac{2H\eta(-\rho_r{}^B+c_n)(1+r_b)+2s^B\phi(-1+q_0)(H-\eta+Hr_b)}{\eta(-1+q_0^2)(\eta-2H(1+r_b))}$, $x^B(\rho_r{}^B, s^B) = \frac{\eta\rho_r{}^B-s^B\phi-\eta c_n+s^B\phi q_0}{-2H+\eta-2Hr_b}$, $p_n{}^B(\rho^B) = \frac{\alpha+\beta(c_n+\rho^B)}{2\beta}$. *Substituting those into Equation (1), we then obtain the Hessian matrix of* Π_P^N *with respect to* $\rho_r{}^B$, ρ^B, *and* s^B, $M_4 = \begin{bmatrix} -\frac{2H\eta(1+r_b)}{-\eta+2H(1+r_b)} & 0 & -\frac{H\phi(-1+q_0)(1+r_b)}{-\eta+2H(1+r_b)} \\ 0 & -\beta & 0 \\ -\frac{H\phi(-1+q_0)(1+r_b)}{-\eta+2H(1+r_b)} & 0 & -1 \end{bmatrix}$. *When* $H > \frac{2\eta^2}{(4\eta-\phi^2(-1+q_0)^2)(1+r_b)}$ *and* $\eta > \frac{(-1+q_0)^2\phi^2}{4}$, M_4 *is a negative definite matrix. Solving the first order condition of Equation (3) yields* s^{B*}, ρ^{B*}, *and* ρ_r^{B*}. *Substituting these solutions into* $\theta^B(\rho_r{}^B, s^B)$, $x^B(\rho_r{}^B, s^B)$, *and* $p_n{}^B(\rho^B)$ *derives* p_n^{B*}, θ^{B*}, *and* x^{B*}.

Proposition A3. *The Hessian matrix of* Π_M^F *with respect to* θ^F, p_n^F, *and* x^F *can be solved as follows:* $M_5 = \begin{bmatrix} -\frac{1}{2}\eta\psi(-1+q_0^2)^2 & 0 & -\frac{1}{2}\eta\psi(-1+q_0^2) \\ 0 & -2\beta\psi & 0 \\ -\frac{1}{2}\eta\psi(-1+q_0^2) & 0 & -H(1+r_f)\psi^2 \end{bmatrix}$. *When* $H > \frac{\eta(1+r_f)\psi}{2}$, M_5 *is a negative definite matrix. Solving the first order condition of* Π_M^F *yields* $\theta^F(\rho_r{}^F, s^F) = \frac{2H\eta\psi(-\rho_r{}^F+c_n)(1+r_f)-2s^F\phi(-1+q_0)(\eta-H\psi(1+r_f))}{\eta(-1+q_0^2)(\eta-2H\psi(1+r_f))}$, $x^F(\rho_r{}^F, s^F) = \frac{\eta\rho_r{}^F-s^F\phi-\eta c_n+s^F\phi q_0}{\eta-2H\psi-2H\psi r_f}$, $p_n^F(\rho^F) = \frac{\alpha+\beta(c_n+\rho^F)}{2\beta}$. *Substituting those into Equation (5), we then obtain the Hessian matrix of* Π_P^F *with respect to* ρ_r^F, ρ^F, *and* s^F, $M_6 = \begin{bmatrix} -\frac{2H\eta\psi(1+r_f)}{-\eta+2H\psi(1+r_f)} & 0 & -\frac{H\phi\psi(-1+q_0)(1+r_f)}{-\eta+2H\psi(1+r_f)} \\ 0 & -\beta & 0 \\ \frac{H\phi\psi(-1+q_0)(1+r_f)}{\eta-2H\psi(1+r_f)} & 0 & -1 \end{bmatrix}$. *When* $H > \frac{2\eta^2}{\psi(4\eta-\phi^2(-1+q_0)^2)(1+r_f)}$ *and* $\eta > \frac{(-1+q_0)^2\phi^2}{4}$, M_6 *is a negative definite matrix. Solving the first order condition of Equation (5) yields* s^{F*}, ρ^{F*}, *and* ρ_r^{F*}. *Substituting these solutions into* $\theta^F(\rho_r{}^F, s^F)$, $x^F(\rho_r{}^F, s^F)$, *and* $p_n{}^F(\rho^F)$ *derives* p_n^{F*}, θ^{F*}, *and* x^{F*}.

Appendix A.2. Proof of Corollaries A1 and A2

Corollary A1. *We present the proof under the FPF scheme, and the proofs for other models follow a similar procedure and are therefore omitted.*

$\frac{\partial s^{F*}}{\partial q_0} = -\frac{H\eta\phi\psi c_n(1+r_f)(-2\eta^2+4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))}{(2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))^2} < 0$, $\frac{\partial \rho_r{}^{F*}}{\partial q_0} = -\frac{2H\eta\phi^2\psi c_n(-1+q_0)(1+r_f)(\eta-2H\psi(1+r_f))}{(2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))^2} < 0$, $\frac{\partial x^{F*}}{\partial q_0} = \frac{2H\eta^2\phi^2\psi c_n(-1+q_0)(1+r_f)}{(2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))^2} < 0$, $\frac{\partial D_r{}^{F*}}{\partial q_0} = \frac{2H^2\eta^2\phi^2\psi^2c_n(-1+q_0)(1+r_f)^2}{(-2\eta^2+H\psi(4\eta-\phi^2(-1+q_0)^2)(1+r_f))^2} < 0$; $\frac{\partial \theta^{F*}}{\partial q_0} = \frac{4H\psi c_n(1+r_f)(-2\eta^2\phi^2(-1+q_0)^2-2\eta^3q_0+H\psi(4\eta^2q_0+\phi^4(-1+q_0)^4q_0 - \eta\phi^2(-1+q_0)^2(-3+2q_0))(1+r_f))}{(-1+q_0^2)^2(2\eta^2+H\psi(-4\eta+\phi^2(-1+q_0)^2)(1+r_f))^2}$, *if* $\eta >$

$(-1+q_0)^2\phi^2$ *and* $\frac{2\eta^2}{(1+r_f)(4\eta-(-1+q_0)^2\phi^2)\psi} < H < \frac{2\eta^2(q_0\eta+(-1+q_0)^2\phi^2)}{(1+r_f)(4q_0\eta^2-(-1+q_0)^2(-3+2q_0)\eta\phi^2+(-1+q_0)^4q_0\phi^4)\psi}$, *then* $\frac{\partial\theta^{F^*}}{\partial q_0} < 0$, *otherwise* $\frac{\partial\theta^{F^*}}{\partial q_0} > 0$. $\frac{\partial\Pi_P{}^{F^*}}{\partial q_0} = \frac{H^2\eta^2\phi^2\psi^2c_n^2(-1+q_0)(1+r_f)^2}{(-2\eta^2+H\psi(4\eta-\phi^2(-1+q_0)^2)(1+r_f))^2} < 0$, $\frac{\partial\Pi_M{}^{F^*}}{\partial q_0} = -\frac{2H^2\eta^3\phi^2\psi^3c_n^2(-1+q_0)(1+r_f)^2(-\eta+2H\psi(1+r_f))}{(2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))^3} < 0$.

Corollary A2. *We present the proof under the FPF scheme, and the proofs for other models follow a similar procedure and are therefore omitted.*

$\frac{\partial s^{F^*}}{\partial\phi} = \frac{H\eta\psi c_n(-1+q_0)(1+r_f)(-2\eta^2+4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))}{(2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))^2} > 0$, $\frac{\partial\rho_r{}^{F^*}}{\partial\phi} = -\frac{2H\eta\phi\psi c_n(-1+q_0)^2(1+r_f)(\eta-2H\psi(1+r_f))}{(2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))^2} > 0$, $\frac{\partial x^{F^*}}{\partial\phi} = \frac{2H\eta^2\phi\psi c_n(-1+q_0)^2(1+r_f)}{(2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))^2} > 0$, $\frac{\partial D_r{}^{F^*}}{\partial\phi} = \frac{2H^2\eta^2\phi\psi^2c_n(-1+q_0)^2(1+r_f)^2}{(-2\eta^2+H\psi(4\eta-\phi^2(-1+q_0)^2)(1+r_f))^2} > 0$. $\frac{\partial\theta^{F^*}}{\partial\phi} = \frac{4H\eta\phi\psi c_n(-1+q_0)(1+r_f)(-2\eta+3H\psi(1+r_f))}{(1+q_0)(2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))^2}$. *When* $\eta > (-1+q_0)^2\phi^2$, *if* $\frac{2\eta^2}{(1+r_f)(4\eta-(-1+q_0)^2\phi^2)\psi} < H < \frac{2\eta}{3\psi(1+r_f)}$, *then* $\frac{\partial\theta^{F^*}}{\partial\phi} > 0$, *otherwise* $\frac{\partial\theta^{F^*}}{\partial\phi} < 0$. *When* $4(-1+q_0)^2\phi^2 < \eta \leq (-1+q_0)^2\phi^2$, *then* $\frac{\partial\theta^{F^*}}{\partial\phi} < 0$. $\frac{\partial\Pi_P{}^{F^*}}{\partial\phi} = \frac{H^2\eta^2\phi\psi^2c_n^2(-1+q_0)^2(1+r_f)^2}{(-2\eta^2+H\psi(4\eta-\phi^2(-1+q_0)^2)(1+r_f))^2} > 0$, $\frac{\partial\Pi_M{}^{F^*}}{\partial\phi} = -\frac{2H^2\eta^3\phi\psi^3c_n^2(-1+q_0)^2(1+r_f)^2(-\eta+2H\psi(1+r_f))}{(2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))^3} > 0$.

Appendix A.3. Proof of Corollaries A3–A6

Corollary A3. $s^{B^*} - s^{F^*} = \frac{2H\eta^3\phi c_n(-1+q_0)(1+r_b-\psi(1+r_f))}{(-2\eta^2+H(4\eta-\phi^2(-1+q_0)^2)(1+r_b))(-2\eta^2+H\psi(4\eta-\phi^2(-1+q_0)^2)(1+r_f))}$, $\rho_r^{B^*} - \rho_r^{F^*} = \eta c_n\left(\frac{\eta-2H(1+r_b)}{2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b)} - \frac{\eta-2H\psi(1+r_f)}{2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f)}\right)$, $x^{B^*} - x^{F^*} = \eta^2c_n\left(-\frac{1}{2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b)} + \frac{1}{2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f)}\right)$, $D_r{}^{B^*} - D_r{}^{F^*} = \frac{2H\eta^4c_n(-1+\psi-r_b+\psi r_f)}{(-2\eta^2+H(4\eta-\phi^2(-1+q_0)^2)(1+r_b))(-2\eta^2+H\psi(4\eta-\phi^2(-1+q_0)^2)(1+r_f))}$, $\theta^{B^*} - \theta^{F^*} = \frac{4H\eta^2c_n(\eta-\phi^2(-1+q_0)^2)(1+r_b-\psi(1+r_f))}{(-1+q_0^2)(2\eta^2+H(-4\eta+\phi^2(-1+q_0)^2)(1+r_b))(2\eta^2-4H\eta\psi(1+r_f)+H\phi^2\psi(-1+q_0)^2(1+r_f))}$. *In the case of* $r_b \geq r_f$ *or* $r_f > r_b$ *and* $0 < \psi \leq \frac{1+r_b}{1+r_f}$, *there exist* $s^{F^*} > s^{B^*}$, $\rho_r^{F^*} > \rho_r^{B^*}$, $x^{F^*} > x^{B^*}$, $D_r{}^{F^*} > D_r{}^{B^*}$; *if* $\frac{(-1+q_0)^2\phi^2}{4} < \eta < (-1+q_0)^2\phi^2$, *then* $\theta^{B^*} > \theta^{F^*}$, *otherwise,* $\theta^{F^*} > \theta^{B^*}$. *In the case of* $r_f > r_b$, *when* $\frac{1+r_b}{1+r_f} < \psi < 1$ *there exist* $s^{B^*} > s^{F^*}$, $\rho_r^{B^*} > \rho_r^{F^*}$, $x^{B^*} > x^{F^*}$, $D_r{}^{B^*} > D_r{}^{F^*}$; *if* $\frac{(-1+q_0)^2\phi^2}{4} < \eta < (-1+q_0)^2\phi^2$, *then* $\theta^{F^*} > \theta^{B^*}$, *otherwise,* $\theta^{B^*} > \theta^{F^*}$.

Corollary A4. $\rho^{B^*} - \rho^{F^*} = 0$, $p_n^{B^*} - p_n^{F^*} = 0$, $D^{B^*} - D^{F^*} = 0$

Corollary A5. $\Pi_T^{B^*} - \Pi_T^{F^*} = \frac{1}{16}\left(\frac{3\alpha^2}{\beta} - \frac{\alpha^2(2+\psi)}{\beta} - 6\alpha c_n + 2\alpha(2+\psi)c_n + c_n^2(3\beta - \frac{6048(-151+21(-2+q_0)q_0)}{(281-63(-2+q_0)q_0)^2}\right) - c_n^2\left(\beta(2+\psi) + \frac{2016\psi(-160+\psi(361+252\psi-63(-2+q_0)q_0))}{(160+63\psi(-7+(-2+q_0)q_0))^2}\right)\Big)$, *if* $0 < c_n < \hat{c_n}$, *then* $\Pi_T{}^{B^*} > \Pi_T{}^{F^*}$, *otherwise,* $\Pi_T{}^{B^*} < \Pi_T{}^{F^*}$ *where,* $\hat{c_n} = \frac{\alpha}{\beta\left(1+\frac{24\sqrt{14}A_1}{(-281+63(-2+q_0)q_0)(160-441\psi+63\psi(-2+q_0)q_0)}\right)}$. $A_1 = \sqrt{\frac{-2899200+(9924200-4974543\psi)\psi}{\beta} - 63(-2+q_0)q_0\left(-6400+42640\psi-35406\psi^2+63\psi(-40+63\psi)(-2+q_0)q_0\right)}$,

Corollary A6.
$EI^B - EI^F = \frac{H\eta^4 c_n(1+r_b-\psi(1+r_f))}{(-2\eta^2+H(4\eta-\phi^2(-1+q_0)^2)(1+r_b))(-2\eta^2+4H\eta\psi(1+r_f)-H\phi^2\psi(-1+q_0)^2(1+r_f))}$, *if* $r_b \geq r_f$ *or* $r_f > r_b$ *and* $0 < \psi \leq \frac{1+r_b}{1+r_f}$, *then* $EI^B > EI^F$; *if* $r_f > r_b$ *and* $\frac{1+r_b}{1+r_f} < \psi \leq 1$, *then*, $EI^F > EI^B$.

Appendix A.4. Proof of Model Extension

We present the proof under the FPF scheme, and the proofs for other models follow a similar procedure and are therefore omitted.

The Hessian matrix of U_M^{F-FC} with respect to θ^{F-FC}, p_n^{F-FC}, and x^{F-FC} can be solved as follows: $M_7 = \begin{bmatrix} -\frac{1}{2}\eta\psi(-1+q_0^2)^2(1+\mu) & 0 & -\frac{1}{2}\eta\psi(-1+q_0^2)(1+\mu) \\ 0 & -2\beta\psi(1+\mu) & 0 \\ -\frac{1}{2}\eta\psi(-1+q_0^2)(1+\mu) & 0 & -H(1+r_f)\psi^2(1+\mu) \end{bmatrix}$. When $H > \frac{\eta(1+r_f)\psi}{2}$, M_5 is a negative definite matrix. Solving the first order condition of U_M^{F-FC} yields $\theta^{F-FC}({\rho_r}^{F-FC}, s^{F-FC}) = \frac{2H\eta\psi(-{\rho_r}^F+c_n)(1+r_f)-2s^F\phi(-1+q_0)(\eta-H\psi(1+r_f))}{\eta(-1+q_0^2)(\eta-2H\psi(1+r_f))}$, $x^{F-FC}({\rho_r}^{F-FC}, s^{F-FC}) = \frac{\eta{\rho_r}^F-s^F\phi-\eta c_n+s^F\phi q_0}{\eta-2H\psi-2H\psi r_f}$, $p_n^{F-FC}(\rho^{F-FC}) = \frac{\alpha+\beta\left(c_n+\rho^{F-FC}\right)}{2\beta}$. Substituting those into Π_P^{F-FC}, we then obtain the Hessian matrix of Π_P^{F-FC} with respect to ${\rho_r}^{F-FC}$, ρ^{F-FC}, and s^{F-FC}, $M_8 = \begin{bmatrix} \frac{2H\eta(\psi+\mu\psi+\mu\Psi)(1+r_f)}{(1+\mu)(\eta-2H\psi(1+r_f))} & 0 & \frac{H\phi\psi(-1+q_0)(1+r_f)}{\eta-2H\psi(1+r_f)} \\ 0 & \beta(-1-\frac{\mu\Psi}{\psi+\mu\psi}) & 0 \\ \frac{H\phi\psi(-1+q_0)(1+r_f)}{\eta-2H\psi(1+r_f)} & 0 & -1 \end{bmatrix}$. When $H > \frac{2\eta^2(\psi+\mu\psi+\mu\Psi)}{\psi(4\eta\mu\Psi+(1+\mu)\psi(4\eta-\phi^2(-1+q_0)^2))(1+r_f)}$ and $\eta > \frac{(1+\mu)\phi^2(-1+q_0)^2}{4(1+\mu+\mu\Psi)}$, M_8 is a negative definite matrix. Solving the first order condition of Π_P^{F-FC} yields s^{F-FC^*}, ρ^{F-FC^*}, and $\rho_r^{F-FC^*}$. Substituting these solutions into $\theta^{F-FC}({\rho_r}^{F-FC}, s^{F-FC})$, $x^{F-FC}({\rho_r}^{F-FC}, s^{F-FC})$, and $p_n^{F-FC}(\rho^{F-FC})$ derives $p_n^{F-FC^*}$, θ^{F-FC^*}, and x^{F-FC^*}.

Corollary A7. $\frac{\partial s^{F-FC^*}}{\partial\mu} = \frac{2H\eta^2\phi\psi^2\Psi c_n(-1+q_0)(1+r_f)(-\eta+2H\psi(1+r_f))}{\left(\begin{array}{c}(2\eta^2(\psi+\mu\psi+\mu\Psi)-4H\eta\psi(\psi+\mu\psi+\mu\Psi)(1+r_f)\\ +H(1+\mu)\phi^2\psi^2(-1+q_0)^2(1+r_f))\end{array}\right)^2} < 0$, $\frac{\partial {\rho_r}^{F-FC^*}}{\partial\mu} = \frac{2\eta^2\psi\Psi c_n(\eta-2H\psi(1+r_f))^2}{\left(\begin{array}{c}(2\eta^2(\psi+\mu\psi+\mu\Psi)-4H\eta\psi(\psi+\mu\psi+\mu\Psi)(1+r_f)\\ +H(1+\mu)\phi^2\psi^2(-1+q_0)^2(1+r_f))\end{array}\right)^2} < 0$, $\frac{\partial\rho^{F-FC^*}}{\partial\mu} = \frac{\psi\Psi(-\alpha+\beta c_n)}{2\beta(\psi+\mu\psi+\mu\Psi)^2} < 0$, $\frac{\partial x^{F-FC^*}}{\partial\mu} = -\frac{H\eta^2\phi^2\psi^2\Psi c_n(-1+q_0)^2\left(1+r_f\right)}{\left(\begin{array}{c}2\eta^2(\psi+\mu\psi+\mu\Psi)-4H\eta\psi(\psi+\mu\psi+\mu\Psi)\left(1+r_f\right)\\ +H(1+\mu)\phi^2\psi^2(-1+q_0)^2\left(1+r_f\right)\end{array}\right)^2} < 0$, $\frac{\partial {D_r}^{F-FC^*}}{\partial\mu} = -\frac{\mathrm{cn}H^2(-1+q_0)^2(1+r)^2\eta^2\phi^2\psi^3\Psi}{\left(\begin{array}{c}(H(-1+q_0)^2(1+r)(1+\mu)\phi^2\psi^2+2\eta^2(\psi+\mu\psi+\mu\Psi)\\ -4H(1+r)\eta\psi(\psi+\mu\psi+\mu\Psi))\end{array}\right)^2} < 0.$

$\frac{\partial\theta^{F-FC^*}}{\partial\mu} = -\frac{2H\eta\phi^2\psi^2\Psi c_n(-1+q_0)(1+r_f)(-2\eta+3H\psi(1+r_f))}{(1+q_0)(2\eta^2(\psi+\mu\psi+\mu\Psi)-4H\eta\psi(\psi+\mu\psi+\mu\Psi)(1+r_f)+H(1+\mu)\phi^2\psi^2(-1+q_0)^2(1+r_f))^2}$, *if* $\eta > \frac{(-1+q_0)^2(1+\mu)\phi^2\psi}{\psi+\mu\psi+\mu\Psi}$ *and* $\frac{2\eta^2(\psi+\mu\psi+\mu\Psi)}{(1+r_f)\psi((1+\mu)(4\eta-(-1+q_0)^2\phi^2)\psi+4\eta\mu\Psi)} < H < \frac{2\eta}{3\psi+3r_f\psi}$, *then* $\frac{\partial\theta^{F-FC^*}}{\partial\mu} < 0$, *otherwise* $\frac{\partial\theta^{F-FC^*}}{\partial\mu} > 0$.

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Corollary A8.

$$\frac{\partial \Pi_P{}^{F-FC^*}}{\partial \mu} = -\frac{H^2\eta^2\phi^2\psi^3\Psi c_n(-1+q_0)^2\left(1+r_f\right)^2}{\left(\begin{array}{c}2\eta^2(\psi+\mu\psi+\mu\Psi)-4H\eta\psi(\psi+\mu\psi+\mu\Psi)\left(1+r_f\right)\\+H(1+\mu)\phi^2\psi^2(-1+q_0)^2\left(1+r_f\right)\end{array}\right)^2} < 0;\ \frac{\partial \Pi_M{}^{F-FC^*}}{\partial \mu} = \frac{\psi^2\Psi(\frac{\alpha^2}{\beta}-2\alpha c_n+c_n^2B_1))}{8(\psi+\mu\psi+\mu\Psi)^2},$$ *where*

$$B_1 = \beta - \frac{\begin{array}{c}8H\eta^3\psi(\psi+\mu\psi+\mu\Psi)^2\left(1+r_f\right)\left(\eta-2H\psi\left(1+r_f\right)\right)(2\eta^2(\psi+\mu\psi+\mu\Psi)\\-4H\eta\psi(\psi+\mu\psi+\mu\Psi)\left(1+r_f\right)+H\phi^2\psi(2(1+\mu)\psi+3\mu\Psi)(-1+q_0)^2(1+r_f))\end{array}}{\left(\begin{array}{c}(2\eta^2(\psi+\mu\psi+\mu\Psi)-4H\eta\psi(\psi+\mu\psi+\mu\Psi)(1+r_f)\\+H(1+\mu)\phi^2\psi^2(-1+q_0)^2(1+r_f))\end{array}\right)^3},$$ *if* $\eta > \frac{(-1+q_0)^2\phi^2(2(1+\mu)\psi+3\mu\Psi)}{4(\psi+\mu\psi+\mu\Psi)}$ *and* $H \geq \frac{2\eta^2(\psi+\mu\psi+\mu\Psi)}{(1+r_f)\psi(4\eta(\psi+\mu\psi+\mu\Psi)-(-1+q_0)^2\phi^2(2(1+\mu)\psi+3\mu\Psi))}$, *then* $\frac{\partial \Pi_M{}^{F-FC^*}}{\partial \mu} > 0$.

Corollary A9. $\Pi_T{}^{B-FC^*} - \Pi_T{}^{F-FC^*} = \frac{1}{16}(3(\frac{\alpha^2}{\beta} - 2\alpha c_n + c_n^2(\beta - \frac{2016(-26527+2541(-2+q_0)q_0)}{(3779-693(-2+q_0)q_0)^2})) - \frac{\psi(\frac{\alpha^2(28+11\psi)}{\beta}-2\alpha(28+11\psi)c_n+c_n^2(\beta(28+11\psi)+B_2))}{2+11\psi})$, *where* $B_2 = \frac{2016\psi(2+11\psi)(-4480+\psi(-12288+11\psi(5987+2772\psi-693(-2+q_0)q_0)))}{(320+\psi(752+693\psi(-7+(-2+q_0)q_0)))^2}$.

If the unit manufacturing cost satisfies $C(c_n) < 0$, *then* $\Pi_T{}^{B-FC^*} > \Pi_T{}^{F-FC^*}$, *otherwise* $\Pi_T{}^{F-FC^*} > \Pi_T{}^{B-FC^*}$.

$$C(c_n) = \beta c_n + 24\sqrt{14}\sqrt{\frac{\begin{array}{c}\beta c_n^2(-83853(3779-693B_3)^2\psi^5+242(2079B_3(3339B_3\\-393002)+4745435861)\psi^4+176(2079B_3(13713B_3-338878)\\+2843141215)\psi^3+128(68607B_3(70B_3-129)-639980989)\psi^2\\+4371333120B_3\psi+390297600B_3-814909440(56\psi+5))\end{array}}{(3779-693B_3)^2(11\psi+6)(\psi(693(B_3-7)\psi+752)+320)^2}},$$

where $B_3 = (q_0-2)q_0$.

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