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Study on Green Supply Chain Decisions under Different Power Structures

Yonglong Wang, Xinyu Zheng, Jirong Cai

School of Business Administration, Chongqing Technology and Business University, Chongqing, China

ABSTRACT

This paper investigates decision-making issues of green supply chains under alternative power structures. Assuming that the manufacturer and two retailers are fully rational and risk-neutral decision-makers, three game-theoretic models are established corresponding to manufacturer-led dominance, retailer-led dominance and balanced bilateral power, whose equilibrium solutions are derived analytically. Comparative analysis and numerical simulation of the three game models are implemented to identify the impacts of disparate power structures on the decision-making behaviors and profits of upstream and downstream enterprises within the supply chain. The results reveal that the effects of power structures on green technology investment, order quantity and supply chain members' profits are predominantly contingent on consumers' green preference coefficient and the impact coefficient of green technology investment on wholesale price.

KEYWORDS

Green Supply Chain; Different Power Structures; Decision-making Behaviors.

1. INTRODUCTION

Global warming and worsening natural environment pose mounting requirements and challenges to the socioeconomic development of human society. To advance the sustainable and high-quality development of the global economy, the international community has successively released a series of policy documents. For instance, the European Commission unveiled the European Green Deal in December 2019, which maps out a five-year roadmap for green growth covering industry, agriculture, transportation and energy sectors, providing critical guidance for the global economic transition from the traditional development mode toward sustainable development. Furthermore, during the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change held in November 2023, the All-China Environment Federation issued the 2023 Belt and Road Green Supply Chain Cases. The release is of great significance for countries and regions along the Belt and Road Initiative to build a mutually beneficial community with a shared future for green development and develop a green circular economy. Against such a backdrop, enterprises across various industries in China have actively followed the trend of green development. Typical examples include home appliance manufacturers Gree and Midea shifting production toward fluorine-free, energy-efficient inverter air conditioners [1]; automaker BYD specializing in new energy vehicle manufacturing [2,3]; and telecommunications giant Huawei cooperating with the Green Software Alliance to popularize low-power-consumption design technologies.

Core enterprises in supply chains exert prominent guiding effects on the green transformation of their partners [4]. Faced with increasingly diversified power structures, well-defined decision-making schemes can bring extra profits and incentives for corporate green development. In practice, three

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typical power configurations prevail in supply chains. First, upstream-dominated supply chain: upstream firms control bottleneck resources including proprietary technologies, information and raw materials, thereby determining the operational rhythm and efficiency of the whole supply chain [5, 6], represented by Haier Group. Second, downstream-dominated supply chain: downstream retailers take dominant control over supply chain operation and management by virtue of advantages in capital, market information and sales channels [7, 8], such as Walmart and Best Buy. Third, balanced-power supply chain: upstream and downstream participants engage in Nash bargaining based on their respective competitive strengths, exemplified by the cooperation between Seres and Huawei. In practical green supply chain management, upstream manufacturers such as Huawei, Gree and BYD drive the whole supply chain's green transformation by developing and manufacturing environmentally friendly products with higher greenness [9]. By contrast, downstream retailers including Walmart, Suning and Costco stimulate upstream green technology investment and green product production via raising consumers' environmental awareness and encouraging purchases of eco-friendly commodities [10,11]. Accordingly, supply chain participants hold differentiated priorities under distinct power structures: dominant upstream manufacturers focus primarily on the trade-off between costs and benefits of green technology investment, whereas downstream-dominated supply chains attach more importance to how green investment boosts product sales. As a result, power structure stands as a core determinant of green supply chain decisions.

This paper incorporates green technology investment and heterogeneous power structures into a supply chain consisting of one manufacturer and two competing retailers to explore green supply chain decision-making under alternative power configurations. Specifically, the research addresses two core questions: how can the manufacturer balance costs and returns when implementing green development via green technology investment? With fully rational and risk-neutral supply chain members, how do varying power structures affect the optimal decisions and profitability of upstream and downstream firms? To answer these questions, three game-theoretic models corresponding to manufacturer-led, retailer-led and balanced bilateral power are constructed and their analytical equilibrium solutions are derived. Comparative analysis and numerical simulation are further adopted to quantify the impacts of power structures on firms' decision-making behaviors and profits.

2. PROBLEM DESCRIPTION

2.1. Section Headings

This paper investigates a two-echelon green supply chain composed of one manufacturer and two competing retailers. The manufacturer produces green products ordered by retailers through green technology investment and supplies products to both retailers at an identical wholesale price; subsequently, retailers sell the purchased green products to end consumers, as illustrated in Figure 1. On this basis, three game frameworks corresponding to distinct power structures are established, namely manufacturer-led Stackelberg game, retailer-led Stackelberg game, and Nash game with balanced bilateral power, to explore members' optimal decision-making behaviors under the premise that all supply chain participants are risk-neutral.

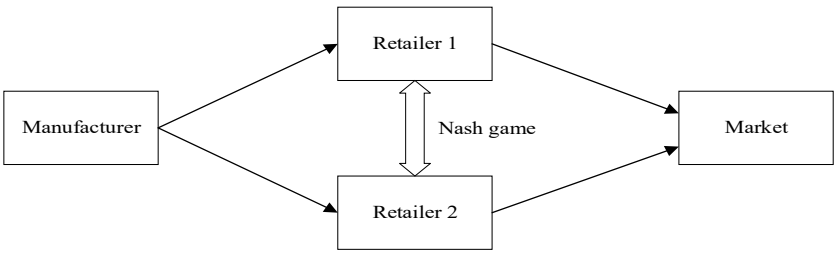


Figure 1. Schematic Diagram of Research Framework

To facilitate model derivation and problem analysis, the following fundamental assumptions are proposed:

Assumption 1: The retail price is affected by sales quantity and green technology investment level, and the inverse demand function is defined as follows [12-14]:

$$\begin{cases} p_1 = A - q_1 - \eta q_2 + ke \\ p_2 = A - q_2 - \eta q_1 + ke \end{cases} \tag{1}$$

where A denotes the potential market scale; η represents the product substitution coefficient between the two retailers, $\eta \in [0,1]$; k is consumers' green preference coefficient.

Assumption 2: The manufacturer's green technology investment positively raises the wholesale price. Without loss of generality, the wholesale price function is set as:

$$w = (1 + he)w_0 \tag{2}$$

where w_0 refers to the baseline wholesale price without any green technology investment; h stands for the influence coefficient of green investment on wholesale price; e indicates the green technology investment level. $C(e) = e^2$ strictly convex cost function is adopted to characterize the manufacturer's expenditure on green R&D investment [15, 16].

Assumption 3: All firms participate in the supply chain only if they can gain positive economic profit. Without loss of generality, relevant constraint conditions are given as $p_i > w > c$ [17, 18], $i \in \{1,2\}$. Here, p_i is retailer i's unit retail revenue, w denotes unit wholesale price, and c represents the manufacturer's unit production cost. All mathematical notations and corresponding definitions used in this chapter are summarized in Table 1.

Table 1. Definitions of Symbols

Notation	Definition	Notation	Definition
e	green technology investment level	p_i	retail price of products for Retailer i
k	retail price of products for Retailer A	q_i	order quantity of Retailer i
h	impact coefficient of green technology investment on wholesale price	π_M^j	manufacturer's profit under Model j
w_0	wholesale price	π_{Ri}^j	profit of Retailer i under Model j
w	wholesale price of green products	MN	manufacturer-led Stackelberg game
η	product substitution coefficient	RN	retailer-led Stackelberg game
A	potential market scale	VN	Nash game with balanced bilateral power
$i \in \{1,2\}$	{Retailer1，Retailer2}		$j \in \{MN, RN, VN\}$

3. ANALYSIS OF GAME MODELS

Differences in power structures alter the decision-making sequence of upstream and downstream firms within the supply chain and further affect their respective profits. Accordingly, this chapter

considers three scenarios of power allocation: manufacturer-dominated supply chain, retailer-dominated supply chain, and balanced power between upstream and downstream participants. Corresponding game models are formulated under the condition that all supply chain members are risk-neutral. Subsequent analyses are conducted for the three proposed game models.

3.1. Manufacturer-led Stackelberg Game Model(MN Model)

Under the MN model, the dynamic game proceeds between a manufacturer and two competing retailers in the following sequence: the manufacturer first determines its green technology investment level e, after which the two retailers simultaneously set their respective order quantities q_1 and q_2. The profit functions of the manufacturer and the two retailers are specified as follows:

$$\begin{cases} \pi_M^{MN} = w_0(1+he)(q_1+q_2) - e^2 \\ \pi_{R1}^{MN} = [A - q_1 - \eta q_2 + ke - (1+he)w_0]q_1 \\ \pi_{R2}^{MN} = [A - q_2 - \eta q_1 + ke - (1+he)w_0]q_2 \end{cases} \tag{3}$$

In the supply chain dominated by the upstream manufacturer, a Stackelberg game is played between upstream and downstream members, while the two downstream retailers engage in a Nash competition. The backward induction method is adopted for model solution, leading to the following proposition.

Proposition 1 Under manufacturer-led dominance, the optimal decisions and corresponding profits of the manufacturer and the two retailers are derived as below:

$$\begin{cases} e^{MN*} = \dfrac{(Ah + k - 2hw_0)w_0}{(\Delta_1)} \\ q_1^{MN*} = q_2^{MN*} = \dfrac{(A - w_0)(2+\eta) + (hw_0 - k)(Ah - k)w_0}{(2+\eta)(\Delta_1)} \\ \pi_M^{MN*} = \dfrac{[2(A - w_0)(2+\eta) + (Ah - k)^2 w_0]w_0}{(2+\eta)(\Delta_1)} \\ \pi_{R1}^{MN*} = \pi_{R2}^{MN*} = \dfrac{[(A - w_0)(2+\eta) + (hw_0 - k)(Ah - k)w_0]^2}{(2+\eta)^2(\Delta_1)^2} \end{cases} \tag{4}$$

Where $\Delta_1 = 2 + \eta - 2hkw_0 + 2h^2 w_0^2$.

3.2. Retailer-led Stackelberg Game Model(RN Model)

Under the RN model, the dynamic game sequence between the manufacturer and two competing retailers is specified as follows: the two retailers simultaneously determine their respective order quantities q_1 and q_2 in the first stage, and then the manufacturer chooses its green technology investment level e. The profit functions of the manufacturer and the two retailers are given as below:

$$\begin{cases} \pi_M^{RN} = w_0(1+he)(q_1+q_2) - e^2 \\ \pi_{R1}^{RN} = [A - q_1 - \eta q_2 + ke - (1+he)w_0]q_1 \\ \pi_{R2}^{RN} = [A - q_2 - \eta q_1 + ke - (1+he)w_0]q_2 \end{cases} \tag{5}$$

When the supply chain is dominated by downstream retailers, upstream and downstream participants conduct a Stackelberg game, whereas the two downstream retailers compete in a Nash game. The backward induction approach is employed to solve the model, yielding the subsequent proposition.

Proposition 2 Under retailer-dominated leadership, the optimal decisions and profits of the manufacturer and the two retailers are expressed as follows:

$$\begin{cases} e^{RN*} = \dfrac{2hw_0(A-w_0)}{(\Delta_1+\Delta_2)} \\ q_1^{RN*} = q_2^{RN*} = \dfrac{2(A-w_0)}{(\Delta_1+\Delta_2)} \\ \pi_M^{RN*} = \dfrac{4w_0(A-w_0)[\Delta_1+\Delta_2+h^2w_0(A-w_0)]}{(\Delta_1+\Delta_2)^2} \\ \pi_{R1}^{RN*} = \pi_{R2}^{RN*} = \dfrac{2(A-w_0)^2(2-hkw_0+h^2w_0^2)}{(\Delta_1+\Delta_2)^2} \end{cases} \tag{6}$$

Where $\Delta_1+\Delta_2 = 4+2\eta-3hkw_0+3h^2w_0^2$.

3.3. Nash Game Model with Balanced Bilateral Power (VN Model)

Under the VN model, no leader–follower relationship exists between the manufacturer and the two competing retailers; all three parties make decisions simultaneously to maximize their individual profits. Specifically, the manufacturer sets its green technology investment level e, Retailer 1 determines its order quantity q_1, and Retailer 2 sets its order quantity q_2. The profit functions for the manufacturer and the two retailers are defined as follows:

$$\begin{cases} \pi_M^{VN} = w_0(1+he)(q_1+q_2)-e^2 \\ \pi_{R1}^{VN} = [A-q_1-\eta q_2+ke-(1+he)w_0]q_1 \\ \pi_{R2}^{VN} = [A-q_2-\eta q_1+ke-(1+he)w_0]q_2 \end{cases} \tag{7}$$

In the scenario of balanced bilateral power, the manufacturer and the two retailers engage in a Nash game, and the two retailers also play a Nash game against each other. Model solving yields the following proposition.

Proposition 3 Under balanced bilateral power, the optimal decisions and profits of the manufacturer and the two retailers are derived as below:

$$\begin{cases} e^{VN*} = \dfrac{hw_0(A-w_0)}{(\Delta_2)} \\ q_1^{VN*} = q_2^{VN*} = \dfrac{A-w_0}{(\Delta_2)} \\ \pi_M^{VN*} = \dfrac{w_0(A-w_0)[\Delta_1+\Delta_2+hkw_0+h^2w_0(A-2w_0)]}{(\Delta_2)^2} \\ \pi_{R1}^{VN*} = \pi_{R2}^{VN*} = \dfrac{(A-w_0)^2}{(\Delta_2)^2} \end{cases} \tag{8}$$

Where $\Delta_2 = 2-hkw_0+h^2w_0^2$.

4. COMPARATIVE ANALYSIS OF GAME MODELS

The equilibrium solutions of the supply chain game under the MN, RN and VN models reveal that the optimal decisions and profits of upstream and downstream supply chain participants vary across

distinct power structures. By comparing the equilibrium outcomes under alternative power configurations, this section explores how power distribution influences decision-making behaviors and profit performance of all supply chain members.

Proposition 4 The manufacturer's optimal green technology investment across different power structures is closely associated with relevant model parameters:

1)If $k - hw_0 > 0$, then $e^{MN*} > e^{RN*} > e^{VN*}$.

2)If $k - hw_0 < 0$, then $e^{VN*} > e^{RN*} > e^{MN*}$.

Proposition 4 implies that when consumers' green preference coefficient is sufficiently large and condition $k > hw_0$ holds, the manufacturer attains the highest green technology investment under manufacturer-led dominance, followed sequentially by the retailer-dominated case and the balanced bilateral-power case. In contrast, when consumers' green preference coefficient is relatively small and condition $k < hw_0$ is satisfied, green investment peaks under the balanced bilateral-power structure, with the retailer-dominated and manufacturer-dominated scenarios ranking second and third respectively.

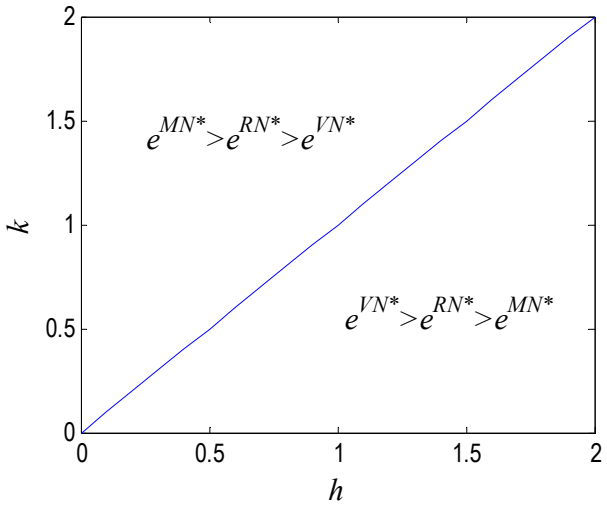


Figure 2. Comparison of Green Technology Investment Levels

Proposition 5 The retailers' equilibrium order quantities under alternative power structures hinge on the interplay among relevant parameters.

1)If $H_1(h,k) > 0$ and $k - hw_0 > 0$, then $q_i^{MN*} > q_i^{RN*} > q_i^{VN*}$.

2)If $H_1(h,k) < 0$ and $k - hw_0 > 0$, then $q_i^{RN*} > q_i^{MN*} > q_i^{VN*}$.

3)If $H_1(h,k) > 0$ and $k - hw_0 < 0$ then $q_i^{MN*} > q_i^{VN*} > q_i^{RN*}, i \in \{1,2\}$.

Where $H_1(h,k) = w_0(hw_0 - k)[(Ah - 2k)(2+\eta) + hw_0(2+\eta - 3Ahk + 3k^2) + 3h^2w_0^2(Ah - k)]$.

Proposition 5 indicates three scenarios: When consumers' green preference coefficient is high alongside conditions $k > hw_0$ and $H_1(h,k) > 0$, retailers' order quantity is the largest under manufacturer dominance, followed by retailer dominance and balanced bilateral power in descending order. When consumers' green preference coefficient remains high but conditions $k > hw_0$ and $H_1(h,k) < 0$ hold, order quantity reaches its maximum under retailer leadership, succeeded by the manufacturer-dominated and balanced-power settings. When consumers' green preference

coefficient is low with conditions $k < hw_0$ and $H_1(h,k) > 0$ satisfied, manufacturer dominance yields the highest retailer order quantity, followed by balanced bilateral power and retailer dominance.

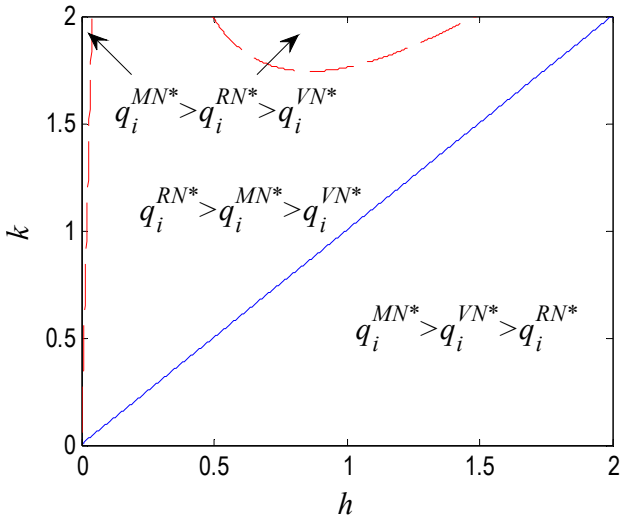


Figure 3. Comparison of Order Quantities

Proposition 6 The manufacturer's profit ranking across diverse power structures is determined by parameters $H_2(h,k)$ and $H_3(h,k)$:

1)If $H_2(h,k) > 0$ and $H_3(h,k) > 0$, then $\pi_M^{MN*} > \pi_M^{RN*} > \pi_M^{VN*}$.

2)If $H_2(h,k) > 0$ and $H_3(h,k) < 0$, then $\pi_M^{MN*} > \pi_M^{VN*} > \pi_M^{RN*}$.

3)If $H_2(h,k) < 0$ and $H_3(h,k) > 0$, then $\pi_M^{RN*} > \pi_M^{MN*} > \pi_M^{VN*}$.

Where $H_2(h,k) = w_0^2(k - hw_0)(h^2 w_0^2(9A^2h^2k + 3k(4 + 3k^2 + 2\eta) - 2Ah[9k^2 + 5(2+\eta)]) + h^3 w_0^3 (4 - 9A^2h^2 + 18Ahk - 9k^2 + 2\eta) - 4(Ah - k)(2+\eta)^2 - 2hw_0(2A^2h^2 - 9Ahk + 6k^2)(2+\eta))$,

$H_3(h,k) = hw_0^2(A - w_0)(k - hw_0)(4(2+\eta)^2 + 2hw_0(2Ah - 5k)(2+\eta) + h^2[-5Ahk + 6(2 + k^2 + \eta)]w_0^2 + h^3(5Ah - 7k)w_0^3 + h^4 w_0^4)$.

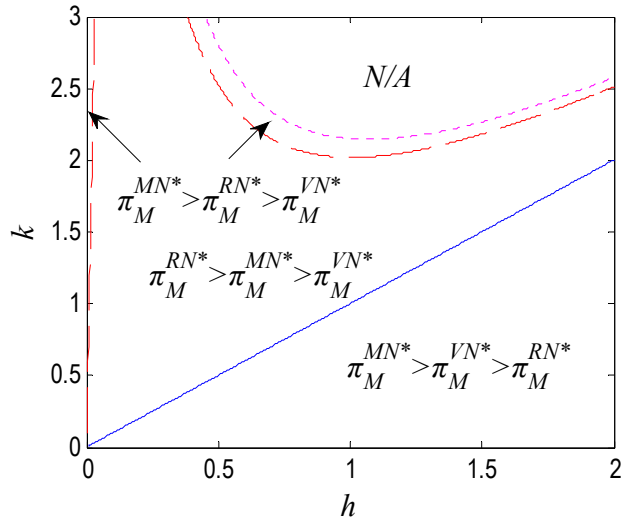


Figure 4. Comparison of Manufacturer's Profits

Proposition 6 demonstrates that when the consumer green preference coefficient and the impact coefficient of green technology investment on wholesale price satisfy constraints $H_2(h,k)>0$ and $H_3(h,k)>0$, the manufacturer achieves the highest profit under manufacturer-dominated structure, followed sequentially by the retailer-dominated scenario and the balanced bilateral-power scenario. When the two aforementioned coefficients satisfy constraints $H_2(h,k)>0$ and $H_3(h,k)<0$, the manufacturer's profit remains the maximum under manufacturer leadership, with the balanced bilateral-power case ranking second and the retailer-dominated case third. When the coefficients meet constraints $H_2(h,k)<0$ and $H_3(h,k)>0$, the manufacturer's profit peaks under retailer dominance, followed by manufacturer dominance and balanced bilateral power in turn.

Proposition 7 The profit level of retailers under different power structures depends on parameters $H_4(h,k)$ and $H_5(h,k)$:

1)If $H_4(h,k)>0$ and $H_5(h,k)>0$, then $\pi_{Ri}^{MN*}>\pi_{Ri}^{RN*}>\pi_{Ri}^{VN*}$.

2)If $H_4(h,k)>0$ and $H_5(h,k)<0$, then $\pi_{Ri}^{MN*}>\pi_{Ri}^{VN*}>\pi_{Ri}^{RN*}$.

3)If $H_4(h,k)<0$ and $H_5(h,k)>0$, then $\pi_{Ri}^{RN*}>\pi_{Ri}^{MN*}>\pi_{Ri}^{VN*}$, $i\in\{1,2\}$.

Where $H_4(h,k)=[A(2+\eta)-(2+Ahk-k^2+\eta)w_0+hw_0^2(Ah-k)]^2(4+2\eta-3hkw_0+3h^2w_0^2)^2-2(A-w_0)^2(2-hkw_0+h^2w_0^2)(2+\eta)^2)(2+\eta-2hkw_0+2h^2w_0^2)^2$,

$H_5(h,k)=hw_0(A-w_0)^2(hw_0-k)[2\eta(2+\eta)-hkw_0(3+4\eta)+h^2w_0^2(3+2k^2+4\eta)-4h^3kw_0^3+2h^4w_0^4]$.

Proposition 7 indicates that when the consumer green preference coefficient and the impact coefficient of green technology investment on wholesale price satisfy constraints $H_4(h,k)>0$ and $H_5(h,k)>0$, retailers obtain the highest profit in the manufacturer-led setting, followed by retailer dominance and balanced bilateral power. When the two coefficients satisfy constraints $H_4(h,k)>0$ and $H_5(h,k)<0$, retailers' profit is maximized under manufacturer dominance, then under balanced bilateral power and retailer dominance. When the coefficients comply with constraints $H_4(h,k)<0$ and $H_5(h,k)>0$, retailers earn the optimal profit under their own dominance, succeeded by manufacturer dominance and balanced bilateral power.

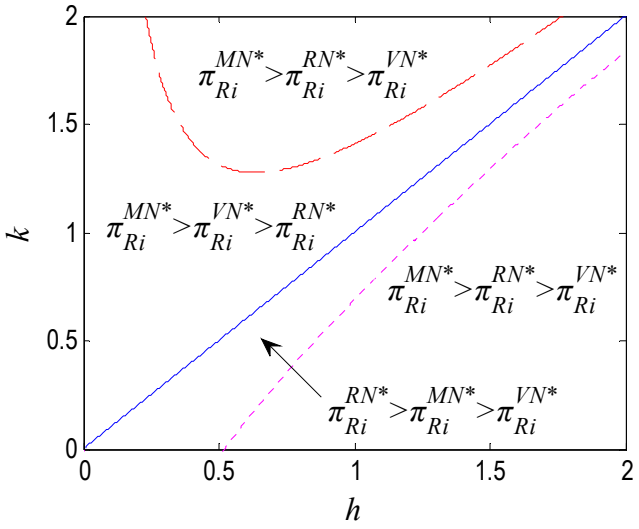


Figure 5. Comparison of Retailers' Profits

5. CONCLUSION

This chapter investigates a two-echelon green supply chain consisting of one manufacturer and two competing retailers. Three game-theoretic models corresponding to alternative power structures are established, namely the manufacturer-led Stackelberg game, the retailer-led Stackelberg game, and the Nash game under balanced bilateral power. Analytical equilibrium solutions are derived for all models. By comparatively analyzing these equilibrium outcomes, this study identifies how varying power configurations affect the decision-making behaviors and profits of supply chain participants. The main findings are summarized as follows:

1)The manufacturer's optimal green technology investment under different power structures is primarily governed by consumers' green preference coefficient and the impact coefficient of green technology investment on wholesale price. Specifically, when parameter condition $k > hw_0$ holds, the manufacturer attains the highest investment under manufacturer dominance and the lowest under balanced bilateral power. When parameter condition $k < hw_0$ holds, the investment peaks under balanced bilateral power and reaches the minimum under manufacturer dominance.

2)The two retailers' equilibrium order quantities across diverse power structures mainly depend on consumers' green preference coefficient and the impact coefficient of green technology investment on wholesale price. To be specific, if constraints $k > hw_0$ and $H_1(h,k) > 0$ are satisfied simultaneously, retailers' order quantity is maximized under manufacturer dominance and minimized under balanced bilateral power. When constraints $k > hw_0$ and $H_1(h,k) < 0$ hold together, order quantity achieves its maximum under retailer dominance and minimum under balanced bilateral power. For the remaining parameter combinations $k < hw_0$ and $H_1(h,k) > 0$, the order quantity is the largest under manufacturer dominance and the smallest under retailer dominance.

3)The profit variation of the manufacturer across power structures is determined by consumers' green preference coefficient and the impact coefficient of green technology investment on wholesale price. Concretely, under combined constraints $H_2(h,k) > 0$ and $H_3(h,k) > 0$, the manufacturer's profit is the highest under manufacturer dominance and the lowest under balanced bilateral power. Under another group of constraints $H_2(h,k) > 0$ and $H_3(h,k) < 0$, manufacturer profit is maximized under manufacturer dominance and minimized under retailer dominance. When constraints $H_2(h,k) < 0$ and $H_3(h,k) > 0$ are satisfied concurrently, profit peaks under retailer dominance and bottoms out under balanced bilateral power.

4)The influence of power structure on retailers' profits follows a similar rule to that on the manufacturer's profit. In detail, under joint constraints $H_4(h,k) > 0$ and $H_5(h,k) > 0$, retailers earn the highest profit under manufacturer dominance and the lowest under balanced bilateral power. Under another set of constraints $H_4(h,k) > 0$ and $H_5(h,k) < 0$, retailers' profit is maximized under manufacturer dominance and minimized under retailer dominance. When constraints $H_4(h,k) < 0$ and $H_5(h,k) > 0$ are satisfied simultaneously, retailers obtain maximum profit under their own dominance and minimum profit under balanced bilateral power.

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