Sustainable Decision-making in a Low-Carbon Supply Chain: Fairness Preferences and Green Investment

Haiyan Zhong¹, Hong Huo¹,*, Xiaoli Zhang², Shenghua Zheng¹, Member, IEEE

¹School of Management, Harbin University of Commerce, Heilongjiang, 150028 China
²Department of Accounting, Harbin Finance University, Heilongjiang, 150030 China

Corresponding author: Hong Huo (13904658991@163.com)

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ABSTRACT This study investigates optimal decisions in a low-carbon supply chain consisting of a manufacturer and a leading retailer considering the green investment and fairness preferences of member firms. Four Stackelberg game decision models are constructed, in which the manufacturer and the retailer engage in green investment separately when the manufacturer has and does not have fairness preferences. The impacts of fairness preferences and green investment on the optimal decision in the low-carbon supply chain are comparatively analysed. The results show that member firms engage in green investment regardless of the presence or absence of fairness preferences and that this behaviour increases the wholesale price, retail price, and market demand of low-carbon products as well as the profits of member firms and the supply chain. A more interesting finding is that the profit growth of member firms and the supply chain due to the manufacturer’s green manufacturing practices is more pronounced than that due to the retailer’s green marketing practices. When the retailer and the manufacturer engage in green investment, the manufacturer’s fairness preferences have different effects on the wholesale price, retail price, market demand, level of green marketing efforts, member enterprises and profits of the supply chain. Therefore, firms should consider the impact of green investment and fairness preferences when making pricing and performance decisions to achieve efficient operation of the whole supply chain and prevent double marginal effects. Finally, the above conclusions are verified through numerical simulation, providing a reference for the decision-making of member firms in a low-carbon supply chain.

INDEX TERMS Green investment behaviour, retailer-led low-carbon supply chain, sense of fairness, sustainable decision-making

I. INTRODUCTION

With the increasingly severe conflicts between human society and the ecological environment, climate deterioration and resource scarcity, people are gradually realizing that environmental protection and sustainable development are key factors in socioeconomic development. The enactment of environmental policies has put pressure on firms to control their carbon emissions, leading them to seek ways to improve the environmental performance of their products. The destruction of the ecological environment also affects people’s lifestyles and consumption behaviours, as evidenced by the attention consumers give to green energy conservation and environmental protection and their increasingly strong preferences for green products [1][2][3]. Consumers’ increasing awareness of environmental protection and the requirements of sustainable development have led to widespread interest in low-carbon supply chains, which consider resource consumption and environmental protection [4][5]. In recent years, retailers have played an important role in green supply chains. Through green supply
chains led by retailers such as Suning (China), Gome (China), and Walmart (USA), retailers usually gain more channel profits than other members of the chain [6]. In the green economy, when firms make decisions, they must pay attention to the interests and survival of other members to ensure the efficient and sustainable development of the whole supply chain [7]. Green investment behaviour includes environmental awareness in manufacturing and marketing management and focuses on environmentally friendly products or services [8]. In the supply chain, manufacturers use environmentally friendly technologies for green innovation and pollution reduction as well as green investment in low-carbon products. For example, Coca Cola, Dell, and Adidas use advanced technologies to generate green products and promote low-carbon products. Retailers have direct contact with end consumers and can carry out targeted green marketing activities; retailers promote low-carbon products to consumers and encourage them to buy such products. For example, Philips uses the “Energy Star” label to promote green technology [9][10]. As firms implement green investment and the market demand increases, the profits of the supply chain and member firms increase continuously; however, firms must pay extra green investment costs. Therefore, the green investment behaviour of enterprises has an impact on the pricing and optimal decision of supply chain members, which is the focus of managers.

To date, relevant studies have confirmed that green investment can promote the market demand for low-carbon products, satisfy consumers’ green preferences, and promote the long-term growth of corporate profits [11][12]. To realize the economic value of supply chain firms, carbon emission reduction plans and green investment should be implemented to increase the sales of low-carbon products. Green investment is becoming an important manifestation of competitive advantage among supply chains. For example, the retail giant Walmart has developed a carbon emission reduction plan to cooperate with suppliers to reduce waste and packaging and protect natural resources, including a goal to achieve 100% recyclable packaging of its own brands by 2025; in addition, the firm conducts green investment promotions to transform the image of existing stores into green and energy-saving stores [13][14]. However, in reality, the imperfect rationality of firms prevails in the decision-making of member firms in the supply chain. Firms are particularly concerned about the fairness of profit distribution in the supply chain. When there is a mismatch between profit and pay, leaders of supply chain member firms may feel a sense of unfairness, which usually impacts their decision-making [15]. The sense of fairness has a great impact on the green investment level and profits of member firms. Therefore, firms are overly concerned about the fairness of profits and utilities, and this behaviour can exacerbate the double marginalization of the supply chain and affect the sustainable development of the economy. For example, Walmart obtains lower wholesale prices through its dominant advantage, leading to suppliers’ preferences regarding fairness in obtaining benefits. Suppliers feel dissatisfied with Walmart’s unfair practices and negotiate fair terms with Walmart. Fairness preferences change firms’ decisions and increase the benefits they receive from the supply chain [16]. Thus, the sense of fairness also affects the decisions of member firms in the green supply chain. Therefore, it is worth further studying how low-carbon supply chain node enterprises make optimal decisions in the context of a sense of fairness and green investment behaviour. The unequal power structure of the supply chain drives firms to pursue fair profits based on the consideration of their own strengths and contributions. With an increase in the fairness preferences coefficient, the benefits gained by firms through green investment will be continuously redistributed among member firms, reducing firms’ motivation to engage in green investment and thus reducing the overall benefits to the supply chain [17][18]. Therefore, to achieve an effective use of resources, it is crucial for supply chains to consider how member firms make optimal decisions when considering fairness preferences and green investment in retailer-led low-carbon supply chains.

Specifically, we address the following problems:
1) How do supply chain members price and make optimal decisions when firms engage in green investment?
2) Do fairness preferences increase the green investment efforts of member firms and the profits of both parties?
3) How do green investment sensitivity and fairness preferences influence firms’ optimal strategies?

The remainder of the paper is organized as follows. Section II comprehensively reviews the literature, analyses the existing research gaps, and outlines the content and innovation of the present study. The problem statement and basic assumptions are presented in Section III. Then, in Sections IV and V, we establish four Stackelberg game profit decision models and solve for their balanced results by backwards recursion. Section VI includes a comparative analysis of the balanced results of different models. The main findings of the present study are summarized in Section VII through numerical simulation analysis. Finally, in Section VIII, the conclusions of the study are presented, and recommendations for future research are provided. The findings of the present study are compared with existing research findings. The present study focuses on addressing the sustainability decisions of green supply chain member firms and integrating green investment and fairness preferences into retailer-led low-carbon supply chain management to help promote coordinated economic and environmental development and create a sustainable, low-carbon supply chain.

II. REVIEW of LITERATURE and MOTIVATIONS

In this section, we review three main areas of literature relevant to the present study, namely, low-carbon supply
chains, supply chains under fairness preferences, and supply chains considering green investment. In addition, we provide the motivation for and highlights of the study.

A. LOW-CARBON SUPPLY CHAIN

With increasing importance attached to environmental issues, low-carbon supply chains have received extensive attention from researchers. Ghosh et al. investigated coordination problems in manufacturer-led green supply chains, established cost-sharing contracts, and analysed the influence of contract parameters on the decisions of supply chain agents in green supply chains [17]. On this basis, Zhou et al. confirmed that cooperative advertising contracts and cooperative advertising emission reduction cost-sharing contracts can be utilized to achieve coordination in manufacturer-led low-carbon supply chains [19]. Regarding retailer-led supply chains, Hu et al. effectively achieved supply chain coordination by designing reasonable contracts [20]. Considering closed-loop supply chains, Mondal et al. studied the impact of different power structures on the optimal green investment decisions by channel members [21].

Considering carbon cap-and-trade regulations, Xu et al. investigated the use of revenue-sharing contracts and two-part tariff contracts to achieve a win-win outcome for supplier-led supply chain members [22]. Considering environmental regulations, Chen et al. studied carbon reduction strategies for two-tier supply chains using differential games [23]. Considering consumers’ green preferences, Dong et al. conducted a comparative analysis of the profits of the manufacturer and the retailer when they invest individually or simultaneously to improve the greenness of products, concluding that simultaneous investment by member firms leads to an increase in corporate profits [24]. In a competitive environment, Zhu et al. examined the pricing decisions for low-carbon products in a supply chain to provide an optimal pricing strategy [25]. Considering government subsidies and retailers’ fairness preferences, Zhang et al. studied pricing decisions in green supply chains in which manufacturers make carbon emission reduction efforts [26].

The above studies have discussed the coordination of green supply chains using contracts, consumer green preferences, and pricing decisions under carbon caps and environmental regulations. Most studies are based on supplier- or manufacturer-led green supply chains, but retailer-led green supply chains are common in practice. In addition, the impact of the green investment and fairness preferences of member firms on low-carbon supply chain decisions is not considered.

B. SUPPLY CHAINS under FAIRNESS PREFERENCES

Studies on supply chains are nearly always based on the rational “economic man”, while decision-makers consider the fairness of income distribution. Ho et al. conducted a series of experiments that showed that people make decisions with certain behavioural preferences [27]. Many researchers have introduced firms’ fairness preferences into supply chain management. Cui et al. and Caliskan et al. studied the impact of firms’ fairness preferences in manufacturer-led supply chains on channel decisions under linear and exponential demand functions [28][29]. Yang et al. showed that when retailers have fairness preferences, cooperative advertising strategies can be used to achieve supply chain coordination under certain conditions [30]. Chen et al. developed decentralized decision-making models under two types of behavioural concerns—fairness concerns and risk aversion—and derived the optimal strategy for each member with a Stackelberg game in which the manufacturer acts as the leader [31]. Guan et al. studied manufacturers and retailers with Nash bargaining fairness concerns and used revenue and cost-sharing contracts to achieve supply chain coordination [32]. Zhang et al. examined the optimal decision in low-carbon supply chains under the influence of factors such as consumers’ environmental awareness and retailers’ fairness concerns [33], and Pu et al. proposed a fairness-embedded profit-sharing contract that coordinates the supply chain with fairness concerns to improve the utilities of manufacturers and retailers [34]. Xia et al. incorporated consumer low-carbon awareness and social preferences and investigated the channel members’ decision-making and performance under three scenarios, including a decentralized scenario both with and without a cost-sharing contract as well as a centralized scenario [35]. Jian et al. constructed a Stackelberg game model of centralized decision-making and decentralized decision-making with the manufacturer’s fairness concern based on a consideration of the retailer’s sales effort in a green closed-supply chain [36]. Many researchers have also introduced fairness concerns into the field of supply chain optimization and operation, such as the agricultural supply chain, dual-channel supply chain, and service supply chain, to reveal the impact of fairness preferences on firms’ decisions from various perspectives [6][37].

The above studies have focused on the optimal decisions in supply chains and the coordination of supply chains using relevant contracts considering fairness preferences. However, research on pricing and performance decisions in retailer-led supply chains from the perspective of sustainability and environmental protection is lacking. To fill this research gap, we consider both green investment and fairness preferences to study optimal decisions for sustainable retailer-led low-carbon supply chains.

C. SUPPLY CHAINS with GREEN INVESTMENT

Green investment is a common way to encourage sustainable behaviour and has been incorporated into the theory of sustainable supply chains, and its impact on green supply chain decisions deserves further research attention [38]. Green investment is also known as environmental investment, sustainable manufacturing, social marketing, and ecological marketing [39]. It is a green management process that uses
profitable and sustainable approaches, such as product design, green promotion, green pricing, sales locations, and eco-labelling, to meet the needs of customers and society [40]. Green investment aims to meet consumers’ needs, and it reduces the harmful effects on the environment and maintains an ecological focus in the pricing and distribution of products [41]. Chen et al. pointed out that green marketing increases market demand and that it is an important green management practice that enables low-carbon products to match market demand, ensuring a competitive advantage for firms [42]. In the context of the global advocacy of carbon emissions reduction, many researchers have studied decisions in supply chains that involve green investment and have made some breakthroughs. Zhang et al. investigated the impact of consumer environmental awareness on the order quantity, product pricing strategies, and channel coordination of supply chain firms [43]. Basiri & Heydari studied the coordination of a two-stage green supply chain and used a coordination mechanism to develop green investment strategies and make low-carbon product quality decisions [44]. Jamali & Rasti Barzoki studied dual-channel green supply chains and found that centralized decision-making results in a higher greenness of products than does decentralized decision-making [45]. On this basis, Heydari et al. investigated the optimal decisions of channel members in a three-tier dual-channel green product supply chain [46]. Ehsan Shekarian systematically analysed the structure of closed-loop supply chains by game theory and presented a new and more extensive framework, focusing on the collaboration structure of closed-loop supply chains [47]. The above studies have focused on the decision-making and channel coordination of supply chain sustainability when companies engage in green investment but have not investigated the impact of fairness concerns on supply chain investment decisions. The present study is the first attempt to integrate both green investment and fairness preferences into decision-making on low-carbon supply chain sustainability to further broaden research in the field of supply chains.

Table 1. Studies most related to our research

| Literature | Supply chain | Supply Chain Sustainable Decision |
|------------|--------------|----------------------------------|
|            | Manufactur- | Retailer- | Manufacturer | Retailer | Carbon | Green | Green |
|            | er-led | Retailer-led | fairness preferences | fairness preferences | reduction | manufacturer | marketing |
| [50] [51] [52] [53] | √ | | | | | |
| [42] [33] [34] | | | | | | |
| [27] [28] [21] | √ | | | | | |
| [8] | √ | | | | | |
| [26] | √ | | | | | |
| [40] | | | | | | |
| [54] [52] | | | | | | |
| [6] | | | | | | |
| [38] | | | | | | |
| [25] | | | | | | |
| [5] | | | | | | |
| [34] | | | | | | |
| [31] | | | | | | |
| [32] [35] | | | | | | |
| [17] | | | | | | |
| [24] [29] | | | | | | |
| this paper | | | | | | |

In summary, numerous studies have been carried out on green supply chain decision-making considering either green investment or fairness preferences. However, most of these studies have targeted manufacturer-led green supply chains, considering the green investment efforts of retailers. [8,42,50,52,53,54] focused on the contract coordination of green supply chains but did not consider manufacturers’ fairness preferences, while [6,24,25,31,34,38] considered retailers’ fairness preferences and examined retailer- or manufacturer-led supply chain decision-making and coordination but did not consider green manufacturing or marketing. Table 1 compares the research content in the present study with the existing research findings. The present study focuses on addressing the sustainability decisions of low-carbon supply chain member firms and integrating green manufacturing or marketing and fairness.
preferences into retailer-led green supply chain management to help promote coordinated economic and environmental development and achieve sustainable green supply chain development.

III. MODEL DESCRIPTION and ASSUMPTIONS

This study considers a two-stage low-carbon supply chain composed of a single manufacturer and a single retailer. The retailer is fairness neutral in a leading position in the supply chain, and the manufacturer, in a disadvantaged position, has a sense of fairness. The manufacturer produces low-carbon products, the retailer orders and sells low-carbon products, and both the retailer and manufacturer can engage in green investment behaviour [11][38]. For convenience, the four models examined are described as follows: in Model NM, the manufacturer has no sense of fairness and engages in green manufacturing; in Model NR, the manufacturer has no sense of fairness, and the retailer engages in green marketing; in Model MM, the manufacturer has fairness preferences and engages in green manufacturing; and in Model MR, the manufacturer has a sense of fairness, and the retailer engages in green marketing. The retailer is the leader of the Stackelberg game, with complete information, and the manufacturer is the follower. The operation process of the low-carbon supply chain is shown in Figure 1.

![Figure 1. Two-level low-carbon supply chain theoretical model.](image)

We make the following assumptions to make the models more realistic and economically feasible. Table 2 summarizes the definitions of symbols used in the article.

| Parameters       | The Definitions of Parameters                                                                 |
|------------------|---------------------------------------------------------------------------------------------|
| $q$              | the actual market demand                                                                     |
| $a$              | the potential total market demand                                                             |
| $b$              | the coefficient of demand sensitivity to price                                               |
| $m$              | the retailer’s production unit profit                                                        |
| $\gamma$         | the sensitivity of market demand to green investment efforts                                 |
| $\eta$           | the cost parameter for green investment efforts                                              |
| $c$              | the manufacturer’s unit production cost                                                      |
| $\lambda$        | the manufacturer’s fairness preferences coefficient                                           |
| $\pi'_m$         | the profits of green supply chain member enterprises                                         |
| $U$              | the manufacturer’s utility                                                                   |

| Decision Variables | The Definitions of Decision Variables                                                      |
|--------------------|--------------------------------------------------------------------------------------------|
| $\omega$           | unit wholesale price of the products                                                        |
| $p$                | the retail price of unit product                                                            |
| $e$                | the level of green investment efforts                                                       |

$s \in \{ N M , N R , M M , M R \}$, $j = \{ m , r , s \}$ represents the profits of the manufacturer, the retailer, and the overall supply chain under four scenarios, where the manufacturer has and does not have fairness preferences and the manufacturer and the retailer engage in green investment.

$^b$ The retail price of a unit product can be expressed as $p = \omega + m$.

**Assumption 1.** Market demand function. The market demand for the product is impacted by the firm’s green effort behaviour. The function for the green effort behaviour of the manufacturer and retailer is considered to be linear [48][49].

Considering a consumer preference for low-carbon products, we assume that the higher the level of green investment effort is, the greater the consumer demand for the product is, while the product sales price remains unchanged. Therefore, we use $\gamma e$ to denote the increase in market demand resulting from green effort behaviour [50]. To ensure that the relevant expressions in this article make economic sense, it is assumed that market demand is a linear function of the retail price and the level of green investment effort and that the retailer’s order quantity is equal to the actual market demand.

Similar to the assumptions for the demand function in previous studies [34][51], we establish the market demand function as follows:

$$q(p) = a - bp + \gamma e$$  \hspace{1cm} (1)

**Assumption 2.** The cost of green effort behaviour. The more effort a firm puts into green behaviour, the higher the cost is. As the level of green behaviour efforts increases, so does the market demand. Therefore, we define the cost of green behaviour efforts as $g(e) = \frac{\eta e^2}{2}$, where $\eta$ is a constant in the coefficient for the cost of green behaviour efforts.

Because the sales effort has a certain limit, the cost of green behaviour has economic significance, and without loss of generality, $\eta$ should be large enough [52][4][53].

**Assumption 3.** The utility of the manufacturer’s sense of fairness. Firms are concerned about their own interests as well as the interests of others and compare these interests to determine whether they are fair. The retailer is assumed to be a profit maximizer whose only concern is profit. The retailer plays a Stackelberg game with the manufacturer, who is concerned with distributional fairness only. The manufacturer exhibits distributional fairness concerns when the retailer obtains a larger share of the total profit that they create together. The greater the fairness attention coefficient is, the larger the impact on firm decisions is [22].

According to the sense of fairness model established by Fehr & Schmid based on benefit fairness, agents are more sensitive to losses and have more prominent unfavourable and unfair preferences when there is an equal profit loss [21][54]. Therefore, we use a simplified form that is not essentially different from the general form [55]. Similar assumptions were made in previous research [39]. In a retailer-led green supply chain, then, the utility of the manufacturer’s sense of fairness is $U_m = (1 + \lambda \pi'_m - \lambda \pi_r)$.
and \( \pi_r > \pi_m \), \( 0 \leq \lambda \leq 1 \cdot \lambda \) is the manufacturer’s sense of fairness coefficient.

**Assumption 4.** Assume that the market is a product market in a single period. Both the manufacturer and the retailer deal with a single product and do not consider out-of-stock products. The manufacturer produces a low-carbon product and sells the low-carbon product to the retailer at a wholesale price; the retailer sells the low-carbon product to the consumer at a retail price and earns a per unit profit; and the manufacturer and retailer incur no costs other than the manufacturer’s production cost. Assuming that all member firms of the low-carbon supply chain can carry out green effort behaviour through corporate behaviours, we refer to assumption \( 0 < \gamma < \sqrt{2}\eta \) in previous research to ensure the feasibility of the relevant expression units and the concavity of the general function \[40\].

### IV. DECISION MODEL with GREEN INVESTMENT BEHAVIOUR

#### A. GREEN MANUFACTURING: Model NM

When the manufacturer conducts green manufacturing, in a retailer-led green supply chain, the retailer is fairness-neutral in a leading position in the supply chain, and the manufacturer and the retailer make optimal decisions to maximize profits. The profit functions of the retailer and the manufacturer are expressed as follows \[56\],\[57\].

\[
\pi_m^{NM}(\omega, \epsilon) = (\omega - c)(a - \epsilon(p + \gamma \epsilon)) - \frac{\eta}{2} \epsilon^2
\]

\[
(2) \pi_r^{NM}(p) = (p - \omega)(a - \epsilon(p + \gamma \epsilon)) \tag{3}
\]

Next, we solve this problem by the inverse induction method. Similarly, according to a previous study \[37\], the following decision sequence is used: the retailer first announces the retail price \( \omega \), and the manufacturer then determines the wholesale price \( \epsilon \) and the level of green manufacturing efforts \( \epsilon \) \[56\].

First, we substitute \( p = m + \omega \) into Eq. (2) to obtain

\[
\pi_m^{NM}(\omega, \epsilon) = (\omega - c)[a - \epsilon(m + \omega) + \gamma \epsilon] - \frac{\eta}{2} \epsilon^2 \tag{4}
\]

By solving the first-order and second-order partial derivatives of Eq. (4), we can obtain the Hessian matrix of \( \pi_m^{NM}(\omega, \epsilon) \) as \( H(\pi_m^{NM}) = \begin{bmatrix} -2b & \gamma \\ \gamma & -\eta \end{bmatrix} \). We define \( H_1(\pi_m^{NM}) \) and \( H_2(\pi_m^{NM}) \) as the first-order and second-order leading principal minors of \( H(\pi_m^{NM}) \), respectively. We can obtain that \( |H_1(\pi_m^{NM})| = -2b < 0 \) and \( |H_2(\pi_m^{NM})| = \frac{2\eta - \gamma^2}{4} \). For \( |H_2(\pi_m^{NM})| > 0 \) to be true, then \( 2\eta > \gamma^2 \). According to assumption 4, \( H(\pi_m^{NM}) \) is a negative definite matrix, and \( \pi_m^{NM}(\omega, \epsilon) \) is a strictly concave function of \( \omega \) and \( \epsilon \). Let \( \frac{\partial \pi_m^{NM}(\omega, \epsilon)}{\partial \omega} = 0 \) and \( \frac{\partial \pi_m^{NM}(\omega, \epsilon)}{\partial \epsilon} = 0 \). By solving the binary equations, we can obtain

\[
e^{NM}(m) = \frac{r(a - \epsilon(b - \gamma \epsilon)) - rbm}{2\eta - \gamma^2} \tag{5}
\]

\[
\omega^{NM}(m) = \frac{\alpha \eta - c\gamma^2 + \beta \eta - b\eta \gamma}{2\eta - \gamma^2} \tag{6}
\]

Next, we substitute the results of Eq. (5) and Eq. (6) into Eq. (2). By solving the first-order and second-order derivatives of Eq. (2), we can obtain

\[
\frac{\partial^2 \pi_r^{NM}(m)}{\partial m^2} = -2b < 0 , \text{ so } \pi_r^{NM}(m) \text{ is a strictly concave function of } m \text{; then, we set the first derivative equal to zero from Eq. (2), yielding the optimal } m^{NM*}:
\]

\[
m^{NM*} = \frac{(a - \epsilon b)}{2b} \tag{7}
\]

We substitute the result of Eq. (7) into Eq. (5) and Eq. (6) and obtain the optimal \( e^{NM*} \), \( \omega^{NM*} \), and \( P^{NM*} \). Then, we substitute \( e^{NM*} \) and \( \omega^{NM*} \) into Eq. (1) and obtain \( q^{NM*} \).

The following proposition is obtained.

**Proposition 1:** For the manufacturer conducting green manufacturing, the optimal equilibrium results of the wholesale price, the retail price, the level of manufacturing effort, and the order quantity can be obtained as follows:

\[
\omega^{NM*} = \frac{\eta(a - \epsilon b) + c}{2(2\eta - \gamma^2)} , \quad e^{NM*} = \frac{r(a - \epsilon b)}{2(2\eta - \gamma^2)}
\]

\[
q^{NM*} = \frac{b\eta(a - \epsilon b)}{2(2\eta - \gamma^2)} , \quad P^{NM*} = \frac{(a - \epsilon b)(3\eta - \gamma^2) + c}{2b(2\eta - \gamma^2)}
\]

\[
\pi_r^{NM*} = \frac{\eta(a - \epsilon b)^2}{4(2\eta - \gamma^2)} , \quad \pi_m^{NM*} = \frac{\eta(a - \epsilon b)^2}{8(2\eta - \gamma^2)}
\]

\[
\pi_s^{NM*} = \frac{3\eta(a - \epsilon b)^2}{8(4\eta - \gamma^2)}
\]

#### B. GREEN MARKETING: Model NR

When the retailer conducts green marketing and is fairness-neutral in a retailer-led green supply chain, the manufacturer and the retailer make optimal decisions to maximize profits \[58\]. The profit functions of the retailer and the manufacturer are expressed as follows:

\[
\pi_r^{NR}(p) = (p - \omega)(a - \epsilon(p + \gamma \epsilon))
\]

\[
\pi_m^{NR}(\omega, \epsilon) = (\omega - c)(a - \epsilon(p + \gamma \epsilon)) - \frac{\eta}{2} \epsilon^2
\]

By solving the first-order and second-order partial derivatives of Eq. (8), we can obtain the Hessian matrix of \( \pi_m^{NR}(\omega, \epsilon) \) as \( H(\pi_m^{NR}) = \begin{bmatrix} -2b & \gamma \\ \gamma & -\eta \end{bmatrix} \). We define \( H_1(\pi_m^{NR}) \) and \( H_2(\pi_m^{NR}) \) as the first-order and second-order leading principal minors of \( H(\pi_m^{NR}) \), respectively. We can obtain that \( |H_1(\pi_m^{NR})| = -2b < 0 \) and \( |H_2(\pi_m^{NR})| = \frac{2\eta - \gamma^2}{4} \). For \( |H_2(\pi_m^{NR})| > 0 \) to be true, then \( 2\eta > \gamma^2 \). According to assumption 4, \( H(\pi_m^{NR}) \) is a negative definite matrix, and \( \pi_m^{NR}(\omega, \epsilon) \) is a strictly concave function of \( \omega \) and \( \epsilon \). Let \( \frac{\partial \pi_m^{NR}(\omega, \epsilon)}{\partial \omega} = 0 \) and \( \frac{\partial \pi_m^{NR}(\omega, \epsilon)}{\partial \epsilon} = 0 \). By solving the binary equations, we can obtain

\[
e^{NR}(m) = \frac{r(a - \epsilon(b - \gamma \epsilon)) - rbm}{2\eta - \gamma^2} \tag{9}
\]

\[
\omega^{NR}(m) = \frac{\alpha \eta - c\gamma^2 + \beta \eta - b\eta \gamma}{2\eta - \gamma^2} \tag{10}
\]

Next, we substitute the results of Eq. (9) and Eq. (10) into Eq. (8). By solving the first-order and second-order derivatives of Eq. (8), we can obtain

\[
\frac{\partial^2 \pi_r^{NR}(m)}{\partial m^2} = -2b < 0 , \text{ so } \pi_r^{NR}(m) \text{ is a strictly concave function of } m \text{; then, we set the first derivative equal to zero from Eq. (8), yielding the optimal } m^{NR*}:
\]

\[
m^{NR*} = \frac{(a - \epsilon b)}{2b} \tag{11}
\]

We substitute the result of Eq. (11) into Eq. (9) and Eq. (10) and obtain the optimal \( e^{NR*} \), \( \omega^{NR*} \), and \( P^{NR*} \). Then, we substitute \( e^{NR*} \) and \( \omega^{NR*} \) into Eq. (7) and obtain \( q^{NR*} \).

The following proposition is obtained.

**Proposition 2:** For the retailer conducting green marketing, the optimal equilibrium results of the retail price, the level of manufacturing effort, and the order quantity can be obtained as follows:

\[
\omega^{NR*} = \frac{\eta(a - \epsilon b) + c}{2(2\eta - \gamma^2)} , \quad e^{NR*} = \frac{r(a - \epsilon b)}{2(2\eta - \gamma^2)}
\]

\[
q^{NR*} = \frac{b\eta(a - \epsilon b)}{2(2\eta - \gamma^2)} , \quad P^{NR*} = \frac{(a - \epsilon b)(3\eta - \gamma^2) + c}{2b(2\eta - \gamma^2)}
\]

\[
\pi_r^{NR*} = \frac{\eta(a - \epsilon b)^2}{4(2\eta - \gamma^2)} , \quad \pi_m^{NR*} = \frac{\eta(a - \epsilon b)^2}{8(2\eta - \gamma^2)}
\]

\[
\pi_s^{NR*} = \frac{3\eta(a - \epsilon b)^2}{8(4\eta - \gamma^2)}
\]
\[ \pi_{m}^{NR}(\omega) = (\omega - c)(a - bp + \gamma e) \]  \hspace{1cm} (8)

\[ \pi_{r}^{NR}(p,e) = (p - \omega)(a - bp + \gamma e) - \frac{\eta}{2} e^2 \]  \hspace{1cm} (9)

Similar to the previous section, we use the following decision sequence: the retailer first announces the retail price \( P \) and the level of green marketing efforts \( e \). The manufacturer then determines the wholesale price \( \omega \).

First, we substitute \( P = m + \omega \) into Eq. (8) to obtain

\[ \pi_{m}^{NR}(\omega) = (\omega - c)(a - bm - bm + re) \]  \hspace{1cm} (10)

By solving the first-order and second-order partial derivatives of Eq. (10), we obtain \( \frac{\partial^2 \pi_{m}^{NR}(\omega)}{\partial \omega^2} = -2b < 0 \).

so \( \pi_{m}^{NR}(\omega) \) is a strictly concave function of \( \omega \). Then, we set the first derivative equal to zero from Eq. (10) and obtain

\[ \omega(m,e) = \frac{a - bm + bc + re}{2b} \]  \hspace{1cm} (11)

We substitute the result of Eq. (11) into Eq. (9) to obtain

\[ \pi_{r}^{NR}(m,e) = \frac{m(a - bc + \gamma e - bm) - \eta}{2} e^2 \]  \hspace{1cm} (12)

Next, by solving the first-order and second-order partial derivatives of Eq. (12), we can obtain the Hessian matrix of \( \pi_{r}^{NR}(m,e) \) as \( H(\pi_{r}^{NR}) = \begin{bmatrix} -b & \gamma / 2 \\ \gamma / 2 & -\eta \end{bmatrix} \). Then, \( 4b\eta - \gamma^2 > 0 \).

According to assumption 4, \( H(\pi_{r}^{NR}) \) is a negative definite matrix, and \( \pi_{r}^{NR}(m,e) \) is a strictly concave function of \( m \) and \( e \). Hesse matrices are negative definite matrices, making their first derivative equal to 0, and we find the optimal equilibrium results as follows:

\[ e^{NR*} = \frac{\pi_{r}^{NR}}{4b\eta - \gamma^2} \]  \hspace{1cm} (13)

\[ m^{NR*} = \frac{2\eta(a - bc)}{4b\eta - \gamma^2} \]  \hspace{1cm} (14)

Finally, we substitute the results of Eq. (11) and Eq. (13) into Eq. (14) and Eq. (1) and obtain the optimal \( \omega^{NR*} \), \( p^{NR*} \), and \( q^{NR*} \). Accordingly, Proposition 2 is obtained.

Proposition 2: The retailer conducts green marketing, and the optimal equilibrium results of the wholesale price, the retail price, the level of marketing effort, and the order quantity can be obtained as follows:

\[ e^{NR*} = \frac{\eta(a - bc)}{4b\eta - \gamma^2} \]  \hspace{1cm} (15)

\[ p^{NR*} = \frac{3\eta(a - bc) + c}{4b\eta - \gamma^2} \]  \hspace{1cm} (16)

\[ m^{NR*} = \frac{2\eta(a - bc)}{4b\eta - \gamma^2} \]  \hspace{1cm} (17)

\[ q^{NR*} = \frac{b\eta(a - bc)}{4b\eta - \gamma^2} \]  \hspace{1cm} (18)

V. DECISION MODEL with SENSE of FAIRNESS and GREEN INVESTMENT BEHAVIOUR

A. GREEN MANUFACTURING: Model MM

The manufacturer has a sense of fairness and conducts green manufacturing. In a retailer-led low-carbon supply chain, the retailer is fairness neutral in a leading position in the supply chain, and the manufacturer and the retailer make optimal decisions to maximize profits \([54][59]\). The profit functions of the retailer and the manufacturer are expressed as follows:

\[ \pi_{m}^{MM}(\omega,e) = (\omega - c)(a - bp + \gamma e) - \frac{\eta}{2} e^2 \]  \hspace{1cm} (19)

\[ \pi_{r}^{MM}(p) = (p - \omega)(a - bp + \gamma e) \]  \hspace{1cm} (20)

\[ U^{MM}(\omega,e) = (1 + \lambda)\pi_{m}^{MM} - \lambda\pi_{r}^{MM} \]  \hspace{1cm} (21)

We use a solution similar to that in the previous section, with the following decision sequence: the retailer announces the retail price \( P \). According to the fairness preferences coefficient \( \lambda \), the manufacturer then determines the wholesale price \( \omega \) and the level of green manufacturing efforts \( e \).

First, we substitute \( P = m + \omega \) into Eq. (17) to obtain

\[ U^{MM}(\omega,e) = (1 + \lambda)[(w - c)(a - bm - bw + re) - \frac{\eta}{2} e^2 - \lambda m(a - bm - bw + re)] \]  \hspace{1cm} (22)

By solving the first-order and second-order partial derivatives of Eq. (18), we obtain the Hessian matrix of \( \pi_{m}^{MM}(\omega,e) \) as \( H(U^{MM}) = \begin{bmatrix} -2b(\lambda + 1) & \gamma (\lambda + 1) \\ \gamma (\lambda + 1) & -\eta (\lambda + 1) \end{bmatrix} \).

We define \( H_{1}(\pi_{m}^{MM}) \) and \( H_{2}(\pi_{m}^{MM}) \) as the first-order and second-order leading principal minors of \( H(\pi_{m}^{MM}) \), respectively. Then, \( 2b\eta > \gamma^2 \). According to Assumption 4, \( H(\pi_{m}^{MM}) \) is a negative definite matrix, and \( U_{m}^{MM}(\omega,e) \) is a strictly concave function of \( \omega \) and \( e \). Let \( \frac{\partial U^{MM}(\omega,e)}{\partial \omega} = 0 \) and \( \frac{\partial U^{MM}(\omega,e)}{\partial e} = 0 \). By solving the binary equations, we obtain

\[ e^{MM}(m) = \frac{\gamma[(a - bc)(1 + \lambda) - bm(1 + 2\lambda)]}{(2b\eta - \gamma^2)(1 + \lambda)} \]  \hspace{1cm} (23)
\[ \omega_{MM}^*(m) = \frac{\eta(a + bc)(1 + \lambda) - \gamma^2(c + \lambda m + c\lambda) - bmn}{2b(\eta - \gamma^2)(1 + \lambda)} \quad (20) \]

Next, we substitute the results of Eq. (19) and Eq. (20) and \( p = m + \omega \) into Eq. (16). By solving the first-order and second-order derivatives of Eq. (16), we obtain
\[
\frac{\partial^2 \pi_r}{\partial m^2}(m) = -2b < 0 \quad \text{so} \quad \pi_r^*(m) \quad \text{is a strictly concave function of} \quad m \quad \text{. Then, we set the first derivative equal to zero from Eq. (16), which yields the optimal} \quad m^{\text{MM}^*} = \frac{(a - bc)}{2b} \quad (21) \]

We substitute the result of Eq. (21) into Eq. (19), Eq. (20), and \( p = m + \omega \) and obtain the optimal \( e^{\text{MM}^*}, \omega^{\text{MM}^*}, \) and \( p^{\text{MM}^*} \). Then, we substitute \( e^{\text{MM}^*} \) and \( \omega^{\text{MM}^*} \) into Eq. (1) and obtain \( q^{\text{MM}^*} \). The following proposition is obtained.

**Proposition 3.** The manufacturer has a sense of fairness, and the optimal equilibrium results of the wholesale price, the retail price, the level of manufacturing effort, and the order quantity can be obtained as follows:

\[ \omega^{\text{MM}^*} = \frac{(a - bc)(1 + 2\lambda) - \gamma^2}{2b(1 + \lambda)^2} + c \]
\[ p^{\text{MM}^*} = \frac{(a - bc)(3 + 4\lambda) - (1 + 2\lambda)\gamma^2}{2b(1 + \lambda)^2} + c \]
\[ q^{\text{MM}^*} = \frac{b(1 + 2\lambda)(2b\eta - \gamma^2)^2}{8(1 + \lambda)^2(2b\eta - \gamma^2)^2} + c \]
\[ \pi_r^{\text{MM}^*} = \frac{\eta(a - bc)^2}{4(2b\eta - \gamma^2)}(1 + \lambda) \quad \text{and} \quad \pi_m^{\text{MM}^*} = \frac{\eta(a - bc)^2}{8(1 + \lambda)^2(2b\eta - \gamma^2)}(1 + 2\lambda) \]

**Property 1.** The impact of a sense of fairness on corporate decisions concerning the manufacturer’s green manufacturing practices:

\[ \frac{\partial \omega^{\text{MM}^*}}{\partial \lambda} > 0, \quad \frac{\partial p^{\text{MM}^*}}{\partial \lambda} > 0, \quad \frac{\partial e^{\text{MM}^*}}{\partial \lambda} < 0, \quad \frac{\partial q^{\text{MM}^*}}{\partial \lambda} < 0, \quad \frac{\partial \pi_r^{\text{MM}^*}}{\partial \lambda} < 0, \quad \frac{\partial \pi_m^{\text{MM}^*}}{\partial \lambda} < 0 \]

The proof is given in Appendix A.1.

Property 1 indicates that as the manufacturer’s sense of fairness coefficient \( \lambda \) increases, the wholesale price \( \omega^{\text{MM}^*} \) and the retail price \( p^{\text{MM}^*} \) increase, while the level of green manufacturing efforts \( e^{\text{MM}^*} \), market demand \( q^{\text{MM}^*} \), manufacturer’s profit \( \pi_m^{\text{MM}^*} \), retailer’s profit \( \pi_r^{\text{MM}^*} \), and supply chain profit \( \pi_s^{\text{MM}^*} \) decrease. This result can be easily understood as follows. The manufacturer with a sense of fairness is in a subordinate position in the distribution channel, and there are costs involved in implementing green manufacturing, resulting in an increase in the wholesale price. This increase causes the retailer to increase the sales price, which in turn reduces the market demand for low-carbon products and ultimately leads to a decrease in the profits of the manufacturer, the retailer, and the overall low-carbon supply chain.

**B. GREEN MARKETING: Model MR**

The manufacturer has a sense of fairness, the retailer engages in green marketing, and the retailer is fairness neutral [6][60]. The profit functions of the manufacturer and the retailer can be expressed as follows:

\[ \pi_m^{\text{MR}}(\omega) = (\omega - c)(a - bp + \gamma e) \quad (22) \]
\[ \pi_r^{\text{MR}}(p, e) = (p - \omega)(a - bp + \gamma e) - \frac{\eta}{2} e^2 \quad (23) \]
\[ U^{\text{MR}}(\omega, e) = (1 + \lambda)(\pi_m^{\text{MR}} - \lambda \pi_r^{\text{MR}}) \quad (24) \]

Similar to the previous section, we use the following decision sequence: the retailer first announces the retail price \( p \) and the level of green marketing efforts \( e \) . According to the fairness preferences coefficient \( \lambda \), the manufacturer then determines the wholesale price \( \omega_e \).

First, we substitute \( p = m + \omega \) into Eq. (24) . By solving the first-order and second-order derivatives of Eq. (24), we obtain
\[
\frac{\partial^2 U^{\text{MR}}(\omega, e)}{\partial \omega^2} = -2b(1 + \lambda) < 0 \quad \text{, so} \quad U^{\text{MR}}(\omega, e) \text{ is a strictly concave function of} \quad \omega \quad \text{. Then, we set the first derivative equal to zero from Eq. (24) to obtain}
\]
\[ \omega(m, e) = \frac{1}{2b}\left(\frac{\lambda bm}{1 + \lambda} + a + bc + re - bm\right) \quad (25) \]

We substitute the result of Eq. (25) into Eq. (23) to obtain
\[ \pi_r^{\text{MR}}(m, e) = m\left[a - bm + re - bc - \lambda mb\right] - \frac{\eta}{2} e^2 \quad (26) \]

Next, by solving the first-order and second-order partial derivatives of Eq. (26), we obtain the Hessian matrix of \( \pi_r^{\text{MR}}(m, e) \) as
\[ H(\pi_r^{\text{MR}}) = \begin{bmatrix} -b - \lambda b/(1 + \lambda) & \gamma/2 \\ \gamma/2 & -\eta \end{bmatrix} \]

Then, \( 4b\eta(1 + 2\lambda)\gamma^2(1 + \lambda) > 0 \quad . \) According to Assumption 4, \( H(\pi_r^{\text{MR}}) \) is a negative definite matrix, and \( \pi_r^{\text{MR}}(m, e) \) is a strictly concave function of \( m \) and \( e \), making its first derivative equal to 0. The optimal equilibrium results are as follows:

\[ e^{\text{MR}^*} = \frac{r(1 + \lambda)(a - bc)}{4b\eta(1 + 2\lambda) - \gamma^2(1 + \lambda)} \quad (27) \]
The proof is given in Appendix A.2.

Property 2. The impact of sense of fairness behaviour on corporate decisions concerning the retailer’s green marketing with the manufacturer’s sense of fairness:
\[
\frac{\partial \omega^*}{\partial \lambda} > 0, \quad \frac{\partial p^*}{\partial \lambda} < 0, \quad \frac{\partial e^*}{\partial \lambda} < 0, \quad \frac{\partial q^*}{\partial \lambda} < 0, \quad \frac{\partial \pi^*_r}{\partial \lambda} < 0, \quad \frac{\partial \pi^*_m}{\partial \lambda} < 0.
\]
The proof is given in Appendix A.2.

Property 2 indicates that as the sense of fairness coefficient of the manufacturer increases, the wholesale price \( \omega^* \) and the manufacturer’s profit \( \pi^*_m \) also increase, while the retail price \( p^* \), level of green marketing efforts \( e^* \), market demand \( q^* \), retailer’s profit \( \pi^*_r \), and the supply chain profit \( \pi^* \) decrease. This result is not difficult to understand. The manufacturer with a sense of fairness is upstream in the low-carbon supply chain and hence can effectively increase his/her own profit by increasing the wholesale price. This increase reduces the retailer’s incentive to engage in green marketing and thus the cost of sales effort, thereby lowering the sales price. This behaviour leads to a reduction in market demand and hence a decrease in the profits of the retailer and the low-carbon supply chain.

**Property 3.** The influence of green effort behaviour sensitivity on firm decision-making:
\[
\frac{\partial \omega^*}{\partial \gamma} > 0, \quad \frac{\partial p^*}{\partial \gamma} > 0, \quad \frac{\partial e^*}{\partial \gamma} > 0, \quad \frac{\partial q^*}{\partial \gamma} > 0, \quad \frac{\partial \pi^*_r}{\partial \gamma} > 0, \quad \frac{\partial \pi^*_m}{\partial \gamma} > 0, \quad \frac{\partial \pi^*_s}{\partial \gamma} > 0, \quad \text{and } i = \{NM, NR, MM, MR\}.
\]
The proof is given in Appendix A.3.

Property 3 indicates that regardless of which firm engages in green effort behaviour and whether a sense of fairness is present, the wholesale price \( \omega^* \), retail price \( p^* \), level of green investment effort \( e^* \), market demand \( q^* \), manufacturer’s profit \( \pi^*_m \), retailer’s profit \( \pi^*_r \), and supply chain profit \( \pi^*_s \) will all increase with the market demand sensitivity to green effort behaviour \( \gamma \).

Green effort behaviour increases the cost and price of low-carbon products but, more effectively, promotes the sales of low-carbon products. This behaviour is always beneficial to the decision-making of member firms, and the greater the green sensitivity to green effort behaviour is, the more it promotes an increase in profits. Leading retailers should take effective measures to promote green effort behaviour among firms and to increase the market demand for low-carbon products, thereby forming a virtuous low-carbon circular economy. This conclusion differs from the optimal decision of the manufacturer-led low-carbon supply chain in that the wholesale price is impacted by green sensitivity to green effort behaviour [44].

**VI. ANALYSIS of EQUILIBRIUM RESULTS**

This section comparatively analyses the optimal balance in decision-making under four scenarios, namely, those in which the manufacturer and the retailer engage in green effort behaviour separately when there is and is not a sense of fairness. Through comparative analysis, the impact of green sensitivity to green effort behaviour and the sense of fairness coefficient on the optimal decision of supply chain member firms is analysed from the perspective of the profit maximization of members.

**A. The impact of green investment behaviour on the low-carbon supply chain (NM and NR)**

**Theorem 1.** A comparison of the two scenarios in which the manufacturer and the retailer engage in green investment behaviour shows that when green sensitivity to green investment behaviour satisfies \( 0 < \gamma < \sqrt{2b} \), the following relationship is observed between firms’ decisions:
\[
\omega^*_{NM} < \omega^*_{NR}, \quad p^*_{NR} > p^*_{NM}, \quad e^*_{NR} < e^*_{NM}, \quad q^*_{NR} > q^*_{NM}.
\]
The proof is given in Appendix B.1.
Theorem 1 indicates that compared with the scenario in which the retailer engages in green marketing, the scenario in which the manufacturer engages in green manufacturing leads to a high wholesale price \( \omega_{NM}^* \), high market demand \( q_{NM}^* \), a high level of green manufacturing effort \( e_{NM}^* \), a low sales price \( p_{NM}^* \), and an increase in the wholesale and retail prices caused by the green manufacturing costs paid by the manufacturer. Green manufacturing contributes to an increase in the market demand for low-carbon products, which in turn increases the motivation for green manufacturing efforts.

**Corollary 1.** Based on a comparison between the two scenarios in which green effort behaviour is exhibited by the manufacturer and the retailer, the performance decisions in the low-carbon supply chain have the following relationship: 
\[ \pi_m^{NR*} < \pi_m^{NM*}, \pi_r^{NR*} < \pi_r^{NM*}, \pi_s^{NR*} < \pi_s^{NM*}. \]

The proof is given in Appendix C.1

Corollary 1 indicates that the profits of the manufacturer, retailer, and supply chain when the manufacturer engages in green manufacturing are all greater than when the retailer engages in green marketing. Thus, the manufacturer’s green production is more conducive to an increase in the profits of the member firms and the overall supply chain. It is more important for the leading retailer to take strong measures to encourage the manufacturer to carry out green manufacturing and participate in environmental protection and sustainable development.

**B. The impact of a sense of fairness on the low-carbon supply chain: (MM, NM and NR, MR)**

**Theorem 2.** Based on a comparison of the two scenarios with and without a sense of fairness, the decisions in the low-carbon supply chain where the manufacturer implements green manufacturing have the following relationship: 
\[ e_{MM*}^* < e_{NM*}^*, q_{MM*}^* < q_{NM*}^*, \]

1) When \( 0 \leq \gamma \leq \sqrt{b\eta} \), then 
\[ p_{MM*}^* \geq p_{NM*}^*, \omega_{MM*}^* \geq \omega_{NM*}^*. \]

2) When \( \sqrt{b\eta} < \gamma < \sqrt{2b\eta} \), then 
\[ p_{MM*}^* < p_{NM*}^*, \omega_{MM*}^* < \omega_{NM*}^*. \]

The proof is given in Appendix B.2.

Theorem 2 indicates that in the supply chain where the manufacturer engages in green manufacturing, the green manufacturing effort and market demand in the context of a sense of fairness are smaller than in the context without a sense of fairness. When green sensitivity to green effort behaviour is low, the wholesale and retail prices in the context of a sense of fairness are larger than those in the context without a sense of fairness, with the increase in green sensitivity to green effort behaviour, the wholesale and retail prices in the context of a sense of fairness are lower than in the context without a sense of fairness.

**Corollary 2.** A comparison of the two scenarios with and without a sense of fairness shows the following relationship for performance decisions in the supply chain where the manufacturer engages in green manufacturing: 
\[ \pi_m^{MM*} < \pi_m^{NM*}, \pi_r^{MM*} < \pi_r^{NM*}, \pi_s^{MM*} < \pi_s^{NM*}. \]

The proof is given in Appendix C.2.

Corollary 2 indicates that in the supply chain where the manufacturer engages in green manufacturing, the benefits to the manufacturer, the retailer, and the supply chain in the context of a sense of fairness are all smaller than in the context without a sense of fairness; the sense of fairness reduces the benefits to the manufacturer, the retailer, and the low-carbon supply chain. In addition, a sense of fairness is not conducive to an increase in the profits of member firms and the overall low-carbon supply chain.

**Theorem 3.** Based on a comparison of the two scenarios with and without a sense of fairness, the decisions in the low-carbon supply chain where the retailer performs green marketing have the following relationship: 
\[ \omega_{MR*}^* > \omega_{NR*}^*, p_{MR*}^* < p_{NR*}^*, e_{MR*}^* < e_{NR*}^*, q_{MR*}^* < q_{NR*}^*. \]

The proof is given in Appendix B.3.

Theorem 3 indicates that in the low-carbon supply chain with green marketing by the retailer, the green marketing efforts, market demand, and retail price in the context of a sense of fairness are lower than when the manufacturer has no sense of fairness. However, the wholesale price in the context of a sense of fairness is higher than in the context without a sense of fairness. Because the manufacturer is upstream in the supply chain, the most direct way for the manufacturer to increase its profits is to increase the wholesale price. A higher wholesale price discourages the retailer from green marketing efforts and reduces the market demand for low-carbon products. As the cost of green marketing efforts decreases, the retail price also decreases. Therefore, a sense of fairness in the low-carbon supply chain with green marketing by the retailer is also not conducive to the sales of low-carbon products.

**Corollary 3.** A comparison of the two scenarios with and without a sense of fairness shows the following relationship for performance decisions in the low-carbon supply chain where the retailer engages in green marketing: 
\[ \pi_m^{MR*} > \pi_m^{NR*}, \pi_r^{MR*} < \pi_r^{NR*}, \pi_s^{MR*} < \pi_s^{NR*}. \]

The proof is given in Appendix C.3.

Corollary 3 indicates that in the low-carbon supply chain when the retailer engages in green marketing, the profits of the retailer and the low-carbon supply chain with a sense of fairness are smaller than those without a sense of fairness, and the profit of the manufacturer with a sense of fairness is greater than that without a sense of fairness. Therefore, a sense of fairness is conducive to an increase in the manufacturer’s profit but not to an increase in the profits of the retailer and the overall low-carbon supply chain, and the leading retailer should take effective measures to reduce the manufacturer’s sense of fairness. This conclusion differs from the optimal decision of the manufacturer-led low-
carbon supply chain in that the wholesale price is impacted by the manufacturer’s fairness preferences coefficient [44][39][41].

VII. NUMERICAL SIMULATION and ANALYSIS

To better illustrate the above properties and propositions, we further verify them by numerical analysis in this section. The main parameters are as follows:

\[ a = 400, b = 1, c = 2, \eta = 50 \text{ and } \gamma \in [0,8], \lambda \in [0,1]. \]

In a retailer-led low-carbon supply chain with sense of fairness, we analyse the impact of the sense of fairness coefficient and green sensitivity on low-carbon supply chain pricing and performance when the manufacturer and retailer engage in green effort behaviour. This finding provides a reference for corporate decision-making. The results are verified with numerical examples, as shown in Figures 2 to 7.

![Graphs showing the impact of fairness coefficient \( \gamma \) on various parameters.](image)

**FIGURE 2.** \( \omega^*, p^*, e^*, \text{ and } q^* \) with respect to \( \gamma \) (i = NR, NM).

Figure 2 shows that when there is no sense of fairness, regardless of whether the manufacturer or the retailer engages in green effort behaviour, the wholesale price, retail price, level of green investment efforts, and market demand increase with an increase in green sensitivity to green effort behaviour. Further observation of Figure 2 (a, c, d) shows that regardless of the change in green sensitivity to green effort behaviour, the wholesale price, level of green investment effort efforts, and product demand when the manufacturer engages in green manufacturing are all higher than when the retailer engages in green marketing. From Figure 2 (b), when green sensitivity to green effort behaviour is low, the retail price when the retailer performs green marketing is higher than that when the manufacturer engages in green manufacturing, and when green sensitivity to green effort behaviour is high, the opposite occurs. Therefore, Property 3 and Theorem 1 are partially verified. Green manufacturing contributes to an increase in the market demand for low-carbon products, which in turn increases the motivation for green manufacturing efforts. Therefore, green manufacturing by the manufacturer is more beneficial to the sales of low-carbon products. This conclusion differs from the optimal decision of the manufacturer-led low-carbon supply chain [16][40].
Figure 3 shows that when there are no fairness preferences, regardless of whether the manufacturer or the retailer engages in green investment, the profits of the manufacturer, the retailer, and the supply chain all increase with an increase in the green sensitivity coefficient; these profits are all higher when the manufacturer engages in green manufacturing than when the retailer engages in green marketing, and the greater the green sensitivity is, the greater the difference between the two scenarios is. These results partially verify Property 3 and Corollary 1. Hence, green manufacturing can better promote the benefits of member firms and the overall supply chain than the green marketing can. It is thus more important for the leading retailer to take strong measures to encourage the manufacturer to carry out green manufacturing and participate in environmental protection and sustainable development.

Figure 4. $\omega^i$, $p^i$, $e^i$, and $q^i$ with respect to $\gamma$ ($i = MM; \gamma = 2, 5, \sqrt{50}, 8$).
Figure 4 shows that when there is a sense of fairness and the manufacturer engages in green manufacturing (Figure 4 (a, b)), when the green sensitivity to green effort behaviour is low ($0 \leq \gamma \leq \sqrt{50}$), as the sense of the fairness coefficient increases, both wholesale and sales prices increase and are higher than in the context without a sense of fairness. When the green sensitivity to green effort behaviour is high ($\sqrt{50} \leq \gamma$), the opposite occurs. Under each green sensitivity (Figure 4 (c, d)), both the level of green manufacturing efforts and product demand decrease with an increase in the sense of fairness coefficient and are lower than those without a sense of fairness, thus partially verifying Property 1 and Theorem 2.

Therefore, in a retailer-led low-carbon supply chain, although manufacturers’ green production promotes the promotion of low-carbon products, manufacturers’ sense of fairness to a certain extent reduces the price of products and green efforts, which is even less conducive to the sales of low-carbon products. The leading retailer should take appropriate measures to reduce the fairness concerns of manufacturers. This outcome is different from the results of previous studies on manufacturer-led supply chains [36].

Figure 5 shows that when there are fairness preferences and the manufacturer engages in green manufacturing, as seen on the left side, with an increase in green sensitivity, the profits of the manufacturer, retailer, and supply chain all increase, and as seen on the right side, as the fairness preferences coefficient increases, the profits of the manufacturer, retailer, and supply chain all decrease. The profits of the manufacturer, retailer, and supply chain with fairness preferences are all smaller than those without fairness preferences (NM: $\lambda = 0$), and the greater the green sensitivity is, the larger the difference between the two scenarios is. Therefore, the manufacturer’s fairness preference is not conducive to an increase in the benefits to the manufacturer, retailer, and supply chain; however, the manufacturer’s green manufacturing is beneficial. This finding partially verifies Property 3 and Corollary 2. A sense of fairness is not conducive to an increase in the profits of member firms and the overall low-carbon supply chain. Firms should consider the impact of a sense of fairness and accordingly make effective green manufacturing decisions.
Figure 6 illustrates the manufacturer’s fairness preferences and the retailer’s green marketing. Figure 6 (a) shows that as the fairness preferences coefficient increases, the wholesale price increases and is greater than that when the manufacturer has no fairness preferences (NR: $\lambda = 0$). Figure 6 (b, c, d) moreover shows that as the fairness preferences coefficient increases, the retail price, level of green marketing efforts, and product demand all decrease and are smaller than when a manufacturer has no fairness preferences (NR: $\lambda = 0$). With an increase in green sensitivity, the wholesale and sales prices, level of green marketing efforts, and product demand increase. Therefore, from the perspective of whether to strengthen market competitiveness or implement sustainable development, the green marketing decision of the leading retailer should consider the manufacturer’s fairness preferences and make the optimal decision accordingly to ensure the profit of the green supply chain member firms, thus partially verifying Property 3 and Theorem 3. Therefore, in the retailer-led low-carbon supply chain, although retailers’ green marketing promotes the promotion of low-carbon products, the manufacturers’ sense of fairness to a certain extent reduces the price of products and green efforts, which is even less conducive to the sale of low-carbon products. The leading retailer should take appropriate measures to reduce the fairness concerns of manufacturers. This finding is different from the results of previous studies on manufacturer-led supply chains [36][61].
Figure 7 shows the manufacturer’s fairness preferences and the retailer’s green marketing. The left side shows that without fairness preferences, as green sensitivity increases, the profits of the manufacturer, retailer, and supply chain all increase. Property 3 is thus partially verified. When the retailer engages in green marketing and the manufacturer has fairness preferences, with an increase in the fairness preferences coefficient, the profits of the retailer and supply chain both decrease, while the manufacturer’s profit increases. When the manufacturer has fairness preferences, its profit is larger than when it does not have fairness preferences, while the profits of the retailer and supply chain are smaller in the latter case. Property 2 and Corollary 3 are thus verified. Hence, the retailer’s green marketing is conducive to an increase in the profits of the manufacturer, the retailer, and the overall supply chain, while the manufacturer’s fairness preferences are conducive to an increase in his/her own profit but not to an increase in the benefits of the retailer and the overall supply chain. In actual firm operations, retailers engaging in green marketing must use an effective coordination mechanism to fairly distribute the profits of the green supply chain to reduce the manufacturer’s excessive fairness preferences so that the green supply chain system can operate efficiently and stably.

VIII. CONCLUSIONS

The present study investigates the impact of the sense of fairness and green investment behaviour in a retailer-led low-carbon supply chain, which will affect the sustainability decisions of low-carbon supply chain member firms. Stackelberg game decision models are constructed in which the manufacturer and the retailer engage in green investment behaviour separately when the manufacturer has and does not have a sense of fairness. The impacts of a sense of fairness and green effort behaviour on the optimal decision in the low-carbon supply chain are comparatively analysed. To better understand the research results, we further compare the wholesale price, retail price, level of green behaviour efforts, market demand, and performance of member firms and the low-carbon supply chain under different scenarios.

This paper has the following management implications: 1) When firms engage in green effort behaviour, green effort behaviour is always conducive to increasing wholesale prices, retail prices, level of green behaviour efforts, market demand, and profits of manufacturers, retailers, and the supply chain. With the continuous development of green investment behaviour, compared with the retailer’s green marketing behaviour, the manufacturer’s green manufacturing behaviour is more beneficial for increasing the profit of supply chain member enterprises. 2) A sense of fairness hinders the green investment behaviour of supply chain member enterprises and reduces the demand for low-carbon products. Although a sense of fairness limits retailers’ use of channel advantages to increase profits, it reduces the profit of the overall low-carbon supply chain. 3) Under a sense of fairness, when the manufacturer performs green manufacturing, the sense of manufacturer fairness increases wholesale and sales prices when green sensitivity is low and decreases these prices otherwise; when retailers engage in green marketing, with an increase in the sense of fairness coefficient, the wholesale price increases, while the sales price increases. In short, leading retailers should use an effective coordination mechanism to consider the sense of fairness of members while actively promoting green investment behaviour by member firms to ensure an increase in the profits of member firms and the overall supply chain.
support the efficient operation of the low-carbon supply chain, and facilitate the green and sustainable development of the economy.

The present study has the following limitations. We assumed that the demand function is a linear function of green effort behaviour and product price, thereby limiting the adaptability of the model to some extent. In addition, we considered a two-stage low-carbon supply chain only. Future research should consider low-carbon supply chains with multiple competing retailers and consider the impact of a sense of fairness on firms’ decisions.

APPENDIX
Proofs of properties, theorems, and corollaries.

Appendix A.1. Proof of Property 1
By virtue of Proposition 3, we can obtain that

\[ \frac{\partial \omega_{MM}^*}{\partial \lambda} = \frac{(a - bc)}{2b(1 + \lambda)^2} > 0, \quad \frac{\partial p_{MM}^*}{\partial \lambda} = \frac{(a - bc)}{b(1 + \lambda)^2} > 0, \]

\[ \frac{\partial e_{MM}^*}{\partial \lambda} = -\frac{(a - bc)}{2(2b\eta - \gamma^2)(1 + \lambda)^2} < 0, \]

\[ \frac{\partial q_{MM}^*}{\partial \lambda} = -\frac{(a - bc)}{2(2b\eta - \gamma^2)(1 + \lambda)^2} < 0, \]

\[ \frac{\partial \pi_{MM}^*}{\partial \lambda} = 4\frac{(2b\eta - \gamma^2)(1 + \lambda)^2}{(a - bc)^2} < 0, \]

\[ \frac{\partial \pi_{SS}^*}{\partial \lambda} = 4\frac{(2b\eta - \gamma^2)(1 + \lambda)^2}{(a - bc)^2} < 0, \]

Appendix A.2. Proof of Property 2
From Proposition 4, we can obtain

\[ \frac{\partial \omega_{MR}^*}{\partial \lambda} = \frac{\eta(a - bc)(8b\eta - 3\gamma^2)}{[4b\eta(1 + 2\lambda) - \gamma^2(1 + \lambda)]^2} > 0, \]

\[ \frac{\partial p_{MR}^*}{\partial \lambda} = -3\frac{b^2\eta(a - bc)}{[4b\eta(1 + 2\lambda) - \gamma^2(1 + \lambda)]^2} < 0, \]

\[ \frac{\partial e_{MR}^*}{\partial \lambda} = -4\frac{b\eta\gamma(a - bc)}{[4b\eta(1 + 2\lambda) - \gamma^2(1 + \lambda)]^2} < 0, \]

\[ \frac{\partial q_{MR}^*}{\partial \lambda} = -\frac{b\eta\gamma^2(a - bc)}{4b\eta(1 + 2\lambda) - \gamma^2(1 + \lambda)^2} < 0, \]

\[ \frac{\partial \pi_{MM}^*}{\partial \lambda} = 2\frac{b\eta^2(2\lambda + 1)(5\lambda + 2)(a - bc)^2}{[4b\eta(1 + 2\lambda) - \gamma^2(1 + \lambda)]^3} > 0, \]

\[ \frac{\partial \pi_{SS}^*}{\partial \lambda} = -2\frac{b\eta^2(a - bc)^2}{[4b\eta(1 + 2\lambda) - \gamma^2(1 + \lambda)]^2} < 0, \]

\[ \frac{\partial \pi_{SS}^*}{\partial \lambda} = 2\frac{b\eta^2(a - bc)^2(-4\lambda - 1)\gamma^2}{[4b\eta(1 + 2\lambda) - \gamma^2(1 + \lambda)]^2} < 0, \]

Under the basic assumptions and the Hesse matrix assumption of the manufacturer’s equity preferences, it is easy to obtain \( 8b\eta - 3\gamma^2 > 0, \ a - bc > 0, \)

\[ 4b\eta(1 + 2\lambda) - \gamma^2(1 + \lambda) > 0, \]

\[ 4b\eta(2\lambda + 1) - (5\lambda + 2)\gamma^2 > 0. \]

Appendix A.3. Proof of Property 3
When \( i = NM, \) then

\[ \frac{\partial \omega_{NM}^*}{\partial \gamma} = \frac{\eta(a - bc)}{2b\eta - \gamma^2} > 0, \]

\[ \frac{\partial p_{NM}^*}{\partial \gamma} = -\frac{\eta(a - bc)}{2b\eta - \gamma^2} > 0, \]

\[ \frac{\partial e_{NM}^*}{\partial \gamma} = -\frac{b\eta(a - bc)}{2b\eta - \gamma^2} > 0, \]

\[ \frac{\partial q_{NM}^*}{\partial \gamma} = \frac{b\eta(a - bc)}{2b\eta - \gamma^2} > 0, \]

\[ \frac{\partial \pi_{MM}^*}{\partial \gamma} = \frac{\eta(a - bc)^2}{2b(2b\eta - \gamma^2)} > 0, \]

\[ \frac{\partial \pi_{MM}^*}{\partial \gamma} = \frac{\eta(a - bc)^2}{4b(2b\eta - \gamma^2)} > 0, \]

\[ \frac{\partial \pi_{MM}^*}{\partial \gamma} = \frac{\eta(a - bc)^2}{2b(2b\eta - \gamma^2)} > 0. \]

When \( i = \{NM, NR, MM, MR\}, \) then the proof process is similar, and it is not restated here.

Appendix B.1. Proof of Theorem 1
\[ \omega_{NR}^* - \omega_{NM}^* = \frac{-\eta\gamma^2(a - bc)}{2b(2b\eta - \gamma^2)(4b\eta - \gamma^2)} < 0, \]

\[ p_{NR}^* - p_{NM}^* = \frac{(a - bc)\gamma^2(b\eta - \gamma^2)}{2b(2b\eta - \gamma^2)(4b\eta - \gamma^2)} > 0, \]

\[ e_{NR}^* - e_{NM}^* = \frac{-\gamma^3(a - bc)}{2b(2b\eta - \gamma^2)(4b\eta - \gamma^2)} < 0, \]

\[ q_{NR}^* - q_{NM}^* = \frac{-\eta b\gamma^2(a - bc)}{2b(2b\eta - \gamma^2)(4b\eta - \gamma^2)} < 0, \]

When \( 0 < \gamma < \sqrt{b\eta}, \) then \( p_{NR}^* - p_{NM}^* > 0; \)

\[ 0 < \gamma < \sqrt{2b\eta}. \] Theorem 1 is proved.

Appendix C.1. Proof of Corollary 1
According to formula $\pi_s = \pi_r + \pi_m$, we obtain $\pi^{NR*}_s \leq \pi^{NS*}_r$.

Appendix B.2. Proof of Theorem 2

$\omega^{MM*}_m - \omega^{NM*}_m = \frac{\lambda (a-bc)(b\eta - \gamma^2)}{2b(1+\lambda)(2b\eta - \gamma^2)} > 0$

$\omega^{MM*}_r - \omega^{NM*}_r = \frac{\lambda (a-bc)(b\eta - \gamma^2)}{2b(1+\lambda)(2b\eta - \gamma^2)} > 0$.

When $0 \leq \gamma \leq \sqrt{b\eta}$, then $\omega^{NR*}_m \geq \omega^{NS*}_m$; when $\sqrt{b\eta} > \gamma$, then $\omega^{NR*}_m < \omega^{NS*}_m$.

$e^{MM*}_m - e^{NM*}_m = \frac{-\gamma \lambda (a-bc)}{2(b\eta - \gamma^2)(1+\lambda)} < 0$

$q^{MM*}_m - q^{NM*}_m = \frac{-b\eta \lambda (a-bc)}{2(b\eta - \gamma^2)(1+\lambda)} < 0$.

Appendix C.3. Proof of Corollary 3

$\pi^{MR*}_m - \pi^{NR*}_m = \frac{\eta (a-bc)(b\eta - \gamma^2)}{2(4b\eta - \gamma^2)^2} > 0$.

$\pi^{MR*}_r - \pi^{NR*}_r = \frac{-2b\eta \lambda (a-bc)}{2(4b\eta - \gamma^2)^2} < 0$.

According to the formula $\pi_s = \pi_r + \pi_m$, we obtain $\pi^{NR*}_s - \pi^{NS*}_s < 0$.

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