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RESEARCH ARTICLE

# Research on carbon emission reduction and blockchain investment under different dual-channel supply chains

Yongchang Jiang[1] · Chang Liu[1]

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## Abstract
Based on the consideration that consumers have low-carbon sensitivity and channel preference, a Stackelberg game model dominated by the manufacturer was constructed to study the joint strategies of low-carbon emission reduction and blockchain investment of supply chain members under three models: traditional retailer dual channel, manufacturer's online direct sales dual channel, and third-party e-commerce distribution dual channel. The interaction of different levels of emission reduction and blockchain investment in different dual-channel models was verified through the calculation and simulation analysis of the optimal decision of the supply chain members. The research results showed that the optimal emission reduction of manufacturers and the blockchain investment level of retailers under different dual-channel models are distinguishing, and manufacturers have the highest emission reduction under the dual-channel model of direct online sales; when manufacturers invest the same amount of emission reduction, the traditional retailer dual-channel model can obtain the highest profit. In the process of emission reduction decision-making, there are technology investors and beneficiaries, and the investment level is affected by the dual benefit effect of low-carbon emission reduction and trust and the combined effect of cost input. And the profit of the dual channel of third-party e-commerce distribution is the lowest; the ratio of technology gain to cost investment in the supply chain determines the initiative of low-carbon investment. Meanwhile, there are specific blockchain investment thresholds in different dual-channel modes, and the increase of the threshold value will improve the emission reduction. Besides, emission reduction investment is driven by the manufacturer's profit, and the more the manufacturer's channel accounts for, the higher the emission reduction tends to be. And further from the perspective of profit and emission reduction, it provides a reference for the channel selection and joint emission reduction strategies of the supply chain.

**Keywords** Carbon emission reduction · Blockchain · Stackelberg game · Dual channel · Supply chain decision-making

## Introduction

In recent years, with the rapid intensification of the greenhouse effect and the deterioration of the global climate environment, China, as the world's largest carbon emitter, is actively seeking carbon emission reduction strategies and advocating the development of a low-carbon economy (Cheng et al. 2022; Wang et al. 2021). On November 30, 2015, President Xi Jinping announced at the Paris Climate Conference that China would establish an open and transparent carbon emissions trading market by 2020 and make carbon emissions reach a peak by 2030 (Su et al. 2022). Meanwhile, the deepening of consumers' concept of living green life and their demand for green products also promote enterprises to adopt necessary low-carbon emission reduction strategies to reduce carbon emissions (Singh and Mishra 2022). For example, the study shows that car sharing can reduce private car congestion and greenhouse gas emissions in the city of Paihwa, Pakistan (Ullah et al. 2019). In practice, large enterprises such as Wal-Mart and IKEA have already started to implement carbon labeling technology and have successfully gained a competitive advantage by establishing their energy-saving and environmental protection image by actions such as marketing low-carbon products and promoting low-carbon brands (Sun and Fang 2022; Zhao and Cheng 2016). Hui An et al. argue that higher green logistics performance

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✉ Chang Liu
liuchang_edu@163.com

[1] School of Management, Harbin University of Commerce, Harbin 150028, China

can stimulate trade and business activity and promote economic growth (Hui An et al.2021). Meanwhile, more and more companies have started to adopt a combination of two supply chain distribution models, electronic direct sales channels and traditional retail channels, to sell their products, such as IBM, Dell, and Nike (Yu et al. 2020; Feng et al. 2020). And domestic retailers such as Suning have opened online direct sales and distribution channels based on traditional offline channels, guiding consumers to low-carbon consumption by strengthening the physical store experience and store layout and promotion (Liang and Zhang 2020; Luo et al. 2014). The low-carbon publicity and marketing strategies help enterprises to open up the low-carbon market, shape a green corporate image, and then fulfill their social responsibility (Hou and Sun. 2020). And creating economic value has also become one of the key considerations for enterprises in implementing low-carbon emission reduction.

Under the background of online and offline dual channels parallel and low-carbon emission reduction, the three dual-channel models of a traditional retailer, manufacturer's online direct sales, and third-party e-commerce were established in this paper, and the impact of combination strategies of emission reduction technology investment and blockchain investment on supply chain optimal profit and emission reduction decisions were studied. By comparing the optimal decision-making under different dual-channel modes, the contribution of this paper is to find out the optimal solution for emission reduction investment and blockchain investment and obtain the influence of dual-channel parameters on members' profit distribution and cooperation stability. Further from the perspective of profit and emission reduction, it provides a reference for the channel selection of the supply chain and the joint emission reduction strategy. Finally, the corresponding management inspirations and suggestions were provided. The framework of this paper is organized as follows. The "Literature review" section provides a literature review of blockchain construction and application, blockchain investment decisions in the supply chain, and low-carbon emission reduction decisions in the dual-channel supply chain. The research problem description and key assumptions of the model are made in the "Problem description and model assumptions" section. In the "Model formulation and comparative analysis" section, three decision-making models based on the Stackelberg game under the dual channel are established and theoretical research is carried out through propositions. The "Algorithm analysis" section carries out numerical simulation research by means of quantitative methods to verify the accuracy of the obtained propositions, conducts parameter sensitivity analysis from the perspective of single-factor influence and double-factors interaction, and studies the impact of technical investment under different dual channels on member profits and reductions. Finally, conclusions, managerial implications, study limitations, and future research development are discussed in the "Conclusion" section.

## Literature review

In this section, we review the literature focusing on four issues related to optimizing decision and low-carbon emission reduction and blockchain investment decisions. We first illustrate the related literature on blockchain construction and application in the supply chain and blockchain investment decisions. The literature on low-carbon emission reduction decisons is then analyzed. Finally, the related literature on optimal decision comparison in a dual-channel low-carbon supply chain is reviewed.

### Blockchain construction and application in the supply chain

Tamayo et al. (2009) developed a perfect blockchain-based traceability system for agricultural products to truly achieve effective monitoring of the whole process from "farm to table" and thus ensure the transparency of the agricultural supply chain. And He et al. (2018) studied the optimal decision in three cases: traditional supply chain without emission reduction, individual manufacturer emission reduction, and collaborative supply chain emission reduction. Kim and Laskowski (2018) used ontological tools as a traceability food supply chain blockchain design, using the Ethernet blockchain platform to develop smart contracts that support commodity traceability and analyze the origin of luxury goods in large and complex international supply chains. Liu et al. (2021a) constructed a dual-channel supply chain model and found that inter-channel competition is conducive to improving supply chain profits and social benefits.

### Blockchain investment decisions in the supply chain

Fan et al. (2020) discussed the conditions for manufacturers to implement blockchain based on the consideration of consumers' willingness to traceability and blockchain cost-sharing. Liu et al. (2020) studied the conditions for investing in big data and blockchain technology in the green agricultural supply chain from the perspective of enhancing consumers' trust in the greenness of agricultural products. Liu et al. (2021b) studied the thresholds and conditions for implementing blockchain in green supply chains under the condition that the implementation of blockchain brings value gain. Liu and Li (2022) proposed that investing in blockchain technology can suppress the misreporting behavior of suppliers, analyzed the changes of supply chain equilibrium solutions before and after technology investment, sought the cost investment threshold of blockchain technology under different scenarios, designed revenue-sharing contract and repurchase compensation contract for supply chain coordination, and proposed asymmetric Nash equilibrium negotiation to allocate surplus gains.

## Low-carbon emission reduction decisons in the supply chain

Promoting carbon emission reduction and increasing profits is an important element for companies to carry out strategic upgrading and optimization at present. For example, Jiang and Chen (2016) studied the optimal production, pricing, carbon trading, and green supply chains under centralized and decentralized technology investment strategies and proved that quantity commitment strategies can improve the profits of low-carbon supply chains with strategic customer behavior. Ji et al. (2017) found that joint emission reduction strategies are more profitable for both manufacturers and retailers. Low-carbon promotion helps to achieve emission reduction targets and promote economic development and social progress. Liu (2017) compared and analyzed the optimal solutions for decentralized and centralized agricultural supply chains with and without low-carbon technologies, considering the impact of retail prices and low-carbon technology levels. Wu et al. (2021) analyzed the effect of independent and integrated incentives on the total cost and carbon emission cost of collaborative supply chain operation. Ma et al. (2021) further explored the effects of big data empowerment, consumer reference effects, channel preferences, and corporate altruistic behavior on the optimal decisions and performance of firms with the help of continuous dynamic programming theory.

## Optimal decision comparison in dual-channel low-carbon supply chain

With the rapid development and application of information technology, e-commerce plays an increasingly important role in today's economy and society. For example, Liu et al. (2017) studied the emission reduction performance in the single-channel and exclusive dual-channel cases and found that the implementation of low-carbon strategies depends on parameters such as product substitutability and channel-based demand. And to achieve the optimal strategy for emission reduction in dual-channel supply chains. Wang et al. (2018) investigated carbon emission reduction in a dual-channel supply chain driven by aggregate control and trading regulation and consumer low-carbon preferences. Zhou and Ye (2018) compared the optimal equilibrium strategies under single-channel and dual-channel supply chains and found that compared to single-channel supply chains, the profits and emission reduction efforts of manufacturers in dual-channel supply chains are higher, while the profits and advertising efforts of retailers are lower. Han and Wang (2018) found that the ability of electronic supply chains to respond to consumer preferences for low-carbon products directly affects their operations, and manufacturers' emission reduction behaviors will strive for more. And Xin et al. (2019) found that dual-channel sales are only a better choice for manufacturers and retailers under certain conditions. Therefore, in order to study the emission reduction and profit level of the dual-channel supply chain under different conditions, Kai et al. (2019) proposed an evolutionary game analysis evolutionary stability strategy study of low-carbon strategies for supply chain firms and applied it to four combinations of low-carbon strategies for retailers and manufacturers. Ghosh et al. (2020) found that introducing a dual-channel strategy is profitable when consumer low-carbon preferences are high and initial product emissions are low. Yu et al. (2020) analyzed the impact of emission reduction cost coefficient, advertising effort cost coefficient, and cost-sharing ratio on the profit of a dual-channel supply chain. Xie et al. (2021) investigated the dual-channel of retailers, dual-channel of manufacturers, and mixed dual channels for optimal decisions on carbon emission reduction and pricing, with sensitivity analysis and comparison of three dual-channel models. Wu et al. (2021) established a low-carbon decision model based on online stores and their suppliers and found that the promotion of low-carbon operations is effective when the similarity between online and offline operation modes is high, which is conducive to improving the low-carbon awareness of online shoppers. Zhang and Yu (2021) established a dynamic optimization model of dual-channel supply chain emission reduction to study the impact of low-carbon effect and low-carbon goodwill of products.

From the above literature review, it can be found that implementing a dual-channel supply chain strategy is an effective way for most companies, especially consumer product manufacturers and retailers, to expand their sales channels and market space. Table 1 summarizes the related studies on the low-carbon emission reduction and blockchain investment decisions in different dual-channel supply chains. From the described literature, it can be seen that most of the existing research on low-carbon supply chains combined with blockchain technology investment can be characterized as follows: First, the current research on low-carbon supply chain mainly focuses on the single-channel model or the only dual-channel model, and there is a lack of research on carbon emission reduction and blockchain investment strategies among different dual-channel channels. Second, when researching low-carbon technology investment, there are less considered that the application of blockchain as carbon traceability and low-carbon propaganda technology, as well as the matching strategy of the two technology investment processes. Third, there is also a lack of comprehensive

**Table 1** Comparison of this study with related studies

| Paper | Channel | Blockchain investment | Low-carbon/green supply chain |
|---|---|---|---|
| Liu et al. (2017) | D | / | Y |
| Wang and He (2018) | D | / | Y |
| Zhou and Ye (2018) | D | / | Y |
| Han and Wang (2018) | S | / | Y |
| Xin et al. (2019) | DD | / | Y |
| Ghosh SK et al. (2020) | D | / | Y |
| Fan et al. (2020) | S | I | Y |
| Liu et al. (2020) | S | I | Y |
| Xie et al. (2021) | DD | / | Y |
| Zhang and Yu (2021) | D | / | Y |
| Liu and Li (2022) | S | I | N |
| This study | DD | I | Y |

"I" represents blockchain investment; "Y" represents with low-carbon or green supply chain background; "N" represents without low-carbon or green supply chain background; "D" represents dual-channel supply chains; "S" represents single-channel supply chains; "DD" represents different dual-channel supply chains.

research focusing on the impact of emission reduction and blockchain investment and consumer preferences on emission reduction strategies in various dual-channel models and the influence of multi-parameter interaction on optimal decision-making. Based on the above research background, this paper establishes three dual-channel supply chain emission reduction and marketing decision models based on the low-carbon sensitivity and channel preference of consumers and analyzes the emission reduction strategies and optimal profits of each member under different dual-channel models. The investment decisions of the two technologies and the impact of different dual-channel models are studied, which has theoretical significance for guiding the selection and transformation of low-carbon supplier dual-channel models. It has theoretical implications for guiding the selection and transformation of dual-channel models for low-carbon suppliers.

## Problem description and model assumptions

### Problem description

In this paper, three dual-channel supply chain decision models were constructed for a secondary supply chain structure consisting of an abatement manufacturer and a low-carbon promotion retailer, where the manufacturer is the Stackelberg leader and the retailer is the follower (Xin et al. 2019; Wang et al. 2018). Considering the effects of low-carbon technology investment, blockchain technology promotion and consumer preferences on supply chain members, three decision models of traditional retailer dual channel, manufacturer's online direct sales dual channel, and online distribution dual channel were built (Yang et al. 2018), as shown in Fig. 1. Through a comparative analysis of equilibrium results, the supply chain emission reduction and marketing decisions under different channel models were studied to provide theoretical support for supply chain emission reduction strategies in the context of sustainable development.

### Model assumptions

**Assumption 1** Carbon emissions from retailer sales processes are much lower than those from production and transportation processes, so this paper only assumes that manufacturers make emissions reduction investments because of the constrainment of carbon emissions (Ma et al. 2014). It is assumed that emission reduction investment has no effect on the production cost of the product, and the higher the investment factor, the more difficult it is to reduce emissions (Yang et al.2017).

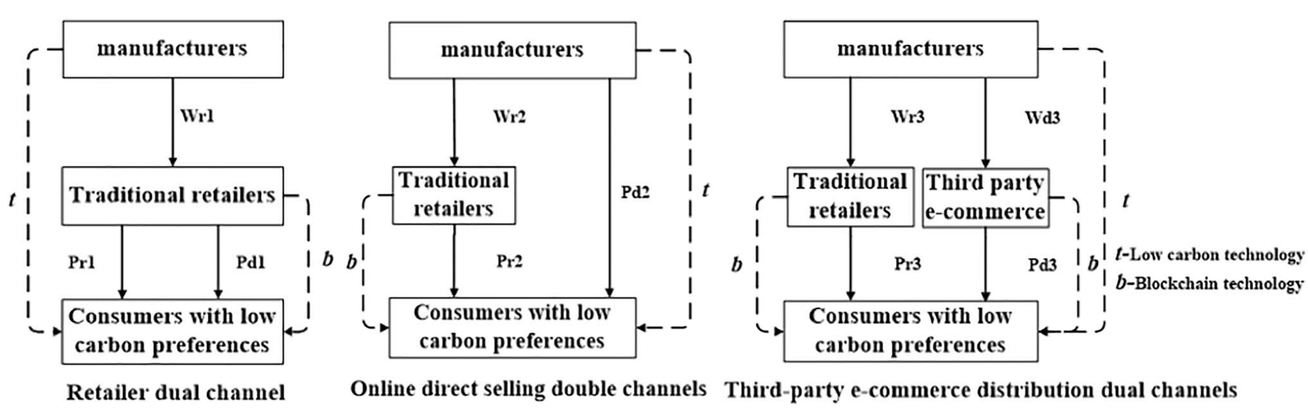



**Fig. 1** Different dual-channel supply chain abatement with blockchain investment models

**Assumption 2** The manufacturer's independent research and development of abatement technology requires investment in technology cost $C_t$. Referring to the cost form of carbon abatement investment with the established assumptions (Zhao et al. 2016), the investment cost $C_t$ is set as a second-order differentiable convex function, i.e.,$C_t = k_\tau t^2/2$, and C(0) = 0, C(+ ∞) = 1, C'(t) > 0, C''(t) > 0, $t$ is the abatement amount, and $k_\tau$ is the abatement cost coefficient. Also, considering that blockchain technology investment is also one of the main factors influencing consumers' purchasing behavior, the blockchain technology investment cost can be set as $I(b) = k_b b^2/2$ and borne by retailers or distributors, $b$ is the blockchain investment level, and $k_b$ is the blockchain cost coefficient (Sun and Fang 2022; Liu et al. 2020).

**Assumption 3** In the analysis of market demand, the impact of emission reduction and blockchain technology investment strategy on product price, market competition, and supply chain profit are considered, and the following demand function can be obtained (Kai et al. 2019; Wang et al. 2018; Han and Wang 2018).

$$d_r = a(1-h) - p_r + \gamma p_d + \eta t + \delta b \tag{1}$$

$$d_d = ah - p_d + \gamma p_r + \eta t + \delta b \tag{2}$$

The demand function takes into account the effects of market volume, dual-channel sales price difference, emission reduction level, and low-carbon publicity, where $r$ and $d$ denote offline and online channels, respectively. $d$ is the market demand, $a$ is the market volume, $h$ is the consumer online channel preference, $p$ is the sales price, $\eta$ and $\delta$ are the low-carbon sensitivity coefficient and blockchain investment coefficient of the product, respectively, and γ represents the price sensitivity coefficient.

**Assumption 4** Consumer demand for a product is more responsive to price changes in its own channel than to price changes of the product in another channel, and the price sensitivity coefficient is set to be symmetric and weakly neutral 0 < γ < 0.4 for the purpose of analysis (Zhao et al. 2016).

## Model formulation and comparative analysis

### Retailer dual-channel model (Model A)

In the retailer dual-channel model, an online marketing channel is introduced by the retailer and the low-carbon products are sold through both offline and online dual channels. In the game process of both sides, firstly, the wholesale price $w_1$ of low-carbon products is decided by the manufacturer, where the product supply prices of both channels are the same; then, based on the wholesale price given by the manufacturer, the sales price $p_{r1}$ and $p_{d1}$ of products in traditional and e-commerce channels are set by the retailer, from which the demand function and decision profit function of the supply chain under the traditional retailer dual-channel model can be obtained as follows (He et al. 2018; Wang et al. 2018; Yang et al. 2018).

The demand function is

$$d_{r1} = a(1-h) - p_{r1} + \gamma p_{d1} + \eta t_1 + \delta b_1 \tag{3}$$

$$d_{d1} = ah - p_{d1} + \gamma p_{r1} + \eta t_1 + \delta b_1 \tag{4}$$

The manufacturer profit function is

$$\Pi_1^M = w_1\left(d_{r1} + d_{d1}\right) - \frac{1}{2}k_\tau t_1^2 \tag{5}$$

Correspondingly, the profit function of the retailer is

$$\Pi_1^S = \left(p_{r1} - w_1\right)d_{r1} + \left(p_{d1} - w_1\right)d_{d1} - \frac{1}{2}k_b b_1^2 \tag{6}$$

**Theorem 1** *The optimal decision for the supply chain under the retailer's dual-channel model is.*

$$w_1^* = \frac{a(3-2h)}{4(1+\gamma)} + \frac{\left(\eta t_1 + \delta b_1\right)}{2(1-\gamma)} \tag{7}$$

$$p_{r1}^* = \frac{a(2h\gamma + 3\gamma - 6h + 7)}{8(1+\gamma)(1-\gamma)} + \frac{3\left(\eta t_1 + \delta b_1\right)}{4(1-\gamma)} \tag{8}$$

$$p_{d1}^* = \frac{a(-6h\gamma + 7\gamma + 2h + 3)}{8(1+\gamma)(1-\gamma)} + \frac{3\left(\eta t_1 + \delta b_1\right)}{4(1-\gamma)} \tag{9}$$

$$d_{r1}^* = \frac{a(5-6h)}{8} + \frac{\left(\eta t_1 + \delta b_1\right)}{4} \tag{10}$$

$$d_{d1}^* = \frac{a(1+2h)}{8} + \frac{\left(\eta t_1 + \delta b_1\right)}{4} \tag{11}$$

$$\Pi_1^M = \frac{a^2(3-2h)^2}{16(1+\gamma)} + \frac{a(3-2h)\left(\eta t_1 + \delta b_1\right)}{4(1+\gamma)(1-\gamma)} + \frac{\left(\eta t_1 + \delta b_1\right)^2}{4(1-\gamma)} - \frac{1}{2}k_\tau t_1^2 \tag{12}$$

$$\Pi_1^S = \frac{a^2\left(-4h^2\gamma + 12h^2 - 24h\gamma - 8h + 29\gamma + 1\right)}{32(1+\gamma)(1-\gamma)} + \frac{a(-4h\gamma + 7\gamma + 1)\left(\eta t_1 + \delta b_1\right)}{8(1+\gamma)(1-\gamma)} + \frac{\left(\eta t_1 + \delta b_1\right)^2}{8(1-\gamma)} - \frac{1}{2}k_b b_1^2 \tag{13}$$

***Proof*** See Appendix.

**Proposition 1** (1) *When* $h < \frac{1}{2}$, $p_{r1}^* > p_{d1}^*$, $d_{r1}^* > d_{d1}^*$, *when* $h > \frac{1}{2}$, $p_{r1}^* < p_{d1}^*$, $d_{r1}^* < d_{d1}^*$; (2) *when* $h < \frac{1}{2}$, $\frac{\partial \Delta p_1^*}{\partial \gamma} < 0$, *when* $h > \frac{1}{2}$, $\frac{\partial \Delta p_1^*}{\partial \gamma} > 0$, (3) $\frac{\partial \Delta p_1^*}{\partial h} < 0$, $\frac{\partial \Delta d_1^*}{\partial h} < 0$.

***Proof:*** (1) $p_{r1}^* - p_{d1}^* = \Delta p_1^* = \frac{a(1-2h)}{2(1+\gamma)}$, $d_{r1}^* - d_{d1}^* = \Delta d_1^* = \frac{a(1-2h)}{2}$; (2) $\frac{\partial \Delta p_1^*}{\partial \gamma} = -\frac{a(1-2h)}{2(1+\gamma)^2}$; (3) $\frac{\partial \Delta p_1^*}{\partial h} = -\frac{a}{(1+\gamma)} < 0$, $\frac{\partial \Delta d_1^*}{\partial h} = -a < 0$.

From Proposition 1, it is clear that under the retailer dual-channel model, consumer channel preference is positively related to the dual-channel selling price $p_{r1}{}^*$ and $p_{d1}{}^*$ and dual-channel demand $d_{d1}{}^*$ and $d_{r1}{}^*$. While the price sensitivity coefficient affects the profitability of supply chain members differently under different consumer preferences. When consumers prefer traditional offline channels more (i.e., $h<0.5$), it can be seen that $\gamma$ is negatively correlated with $\Delta p_1{}^*$ (the price difference between offline and e-commerce channels). Conversely, when the e-commerce channel is dominant (i.e., $h>0.5$), and $\gamma$ is positively correlated with $\Delta p_1{}^*$. In the overall trend, the price differential is negatively correlated with the share of e-commerce channels, and the same is true for the change in the dual-channel demand differential.

**Proposition 2** (1) $\frac{\partial t_1^*}{\partial \eta} > 0$, $\frac{\partial t_1^*}{\partial \delta} > 0$; (2) *when* $k_\tau > \frac{3\eta^2}{2(1-\gamma)}$ 时, $\frac{\partial w_1^*}{\partial \eta} > 0$, $\frac{\partial p_{r1}^*}{\partial \eta} > 0$, $\frac{\partial p_{d1}^*}{\partial \eta} > 0$; (3) $\frac{\partial \Pi_1^S}{\partial t_1} > 0$, $\frac{\partial^2 \Pi_1^S}{\partial t_1^2} > 0$; (3) $\frac{\partial \Pi_1^S}{\partial t_1} > 0$, $\frac{\partial^2 \Pi_1^S}{\partial t_1^2} > 0$; (4) *the existence of an abatement cost factor threshold* $k_\tau' = \frac{\eta^2}{4(1-\gamma)}$, *when* $k_\tau > k_\tau'$, *there exists an optimal amount of emission reduction* $t_1^* = \frac{a(3-2h)+2\delta b_1}{2\left(2\frac{k_\tau}{\eta}(1-\gamma)-\eta\right)}$ *such that the manufacturer's profit* $\Pi_1^M$ *reaches the optimal value.*

***Proof:*** (1) $\frac{\partial t_1^*}{\partial \eta} = \frac{1+2k_\tau(1-\gamma)}{2\left(2k_\tau(1-\gamma)-\eta^2\right)^2} > 0$, the same reason can be proven $\frac{\partial t_1^*}{\partial \delta} > 0$; (2) $\frac{\partial p_{r1}^*}{\partial \eta} = \frac{a(3-2h)\left(2\frac{k_\tau}{\eta}(1-\gamma)-3\eta\right)}{4\left(2\frac{k_\tau}{\eta}(1-\gamma)-\eta\right)^2}$, when $k_\tau > \frac{3\eta^2}{2(1-\gamma)}$, $\frac{\partial p_{r1}^*}{\partial \eta} > 0$, the same reason can be proven $\frac{\partial w_1^*}{\partial \eta} > 0$, $\frac{\partial p_{d1}^*}{\partial \eta} > 0$; (3) $\frac{\partial \Pi_1^S}{\partial t_1} = \frac{a(-4h\gamma+7\gamma+1)}{8(1-\gamma)(1+\gamma)}\eta + \frac{\eta}{4(1-\gamma)}\left(\eta t_1 + \delta b_1\right) > 0$, $\frac{\partial^2 \Pi_1^S}{\partial t_1^2} = \frac{\eta^2}{4(1-\gamma)} > 0$; (4) $\frac{\partial \Pi_1^M}{\partial t_1} = \frac{a(3-2h)}{4(1-\gamma)(1+\gamma)}\eta + \frac{\eta}{4(1-\gamma)}\left(\eta t_1 + \delta b_1\right) - k_\tau t_1$ when $\frac{\partial^2 \Pi_1^M}{\partial t_1^2} < 0$, $\frac{\partial \Pi_1^M}{\partial t_1} = 0$, $t_1^* = \frac{a(3-2h)+2\delta b_1}{2\left(2\frac{k_\tau}{\eta}(1-\gamma)-\eta\right)}$, $\Pi_1^M$ reaches the optimal value.

From Proposition 2, it is clear that in the retailer dual-channel model, consumers' low-carbon preferences positively affect both $w_1{}^*$ and $p_{r1}{}^*$ and $p_{d1}{}^*$; thus, the profit level is increased. Emission reduction $t$ is concave and convexly correlated with $\Pi_1^S$ and $\Pi_1^M$, respectively, and the nonlinearity of emission reduction on profit enhancement is mainly influenced by the investment. Considering that the manufacturer needs to bear the cost of emission reduction, when $\frac{\eta^2}{4(1-\gamma)} < k_\tau$, there exists an optimal amount of emission reduction $t_1{}^*$ for the manufacturer to optimize its profit. It can be seen that the sensitivity of consumer emission reduction and publicity will promote the manufacturer's motivation to reduce emissions and promote its better implementation of carbon emission reduction. Also, increasing investment in blockchain technology will increase consumer trust, which in turn will have a positive impact on manufacturers' carbon emission reductions.

**Proposition 3** (1) $\frac{\partial b_1^*}{\partial \delta} > 0$, $\frac{\partial b_1^*}{\partial \eta} > 0$; (2) $\frac{\partial w_1^*}{\partial \delta} > 0$, $\frac{\partial p_{r1}^*}{\partial \delta} = \frac{\partial p_{d1}^*}{\partial \delta} > 0$, $\frac{\partial d_{r1}^*}{\partial \delta} = \frac{\partial d_{d1}^*}{\partial \delta} > 0$; (3) $\frac{\partial \Pi_1^M}{\partial b_1} > 0$, $\frac{\partial^2 \Pi_1^M}{\partial b_1^2} > 0$;; (4) *the existence of a blockchain cost coefficient threshold* $k_b' = \frac{\delta^2}{4(1-\gamma)}$, *when* $k_b > k_b'$, *there exists an optimal amount of blockchain investment* $b_1^* = \frac{a(-4h\gamma+7\gamma+1)}{2(1+\gamma)\left(4k_b(1-\gamma)-\delta^2\right)} + \frac{\delta\eta t_1}{\left(4k_b(1-\gamma)-\delta^2\right)}$, *which makes the retailer's profit* $\Pi_1^S$ *reach the optimal value.*

***Proof:*** The proof process is the same as that of Proposition 2.

Proposition 3 shows that the impact of the level of low-carbon marketing promotion on price, demand, and profit level is similar to the trend of emission reduction investment. By increasing the low-carbon publicity, it will increase the selling price and demand and boost the manufacturer's profit. Also, considering the cost of publicity, when $k_b > k_b'$, there exists an optimal level of marketing publicity $b_1{}^*$ for retailers to optimize their profits, where $b_1{}^*$ is also proportional to the emission reduction $t$. Besides, low-carbon emission reduction and marketing promotion promote each other.

## Manufacturer's online direct sales dual-channel model (Model B)

In the manufacturer's online direct sales dual-channel model, two sales pathways exist for the manufacturer. Route 1: Low-carbon products are produced by the manufacturer to supply to offline retailers, who sell to consumers based on emission reduction promotion; Route 2: The manufacturer also takes on the role of e-merchants and sells directly to consumers through the online route. At this point, the demand function is not only related to the emission reduction efforts and blockchain investment but also related to the sales price of the dual-channel products. In the game process, firstly, the offline channel supply price $w_{r2}$ and the wholesale price $p_{d2}$ of low-carbon products in the online direct sales channel are decided, and then the carbon emission reduction level $t_2$ is decided by the manufacturer; secondly, based on the wholesale price $w_{r2}$ given by the manufacturer, the offline sales price $p_{r2}$ and the offline channel blockchain technology investment $b_2$ are set by retailer. The demand function and decision profit function of the supply chain under the manufacturer's online direct sales dual-channel model can be obtained as follows (Wang et al. 2018; Xin et al. 2019):

The demand function is

$$d_{r2} = a(1-h) - p_{r2} + \gamma p_{d2} + \eta t_2 + \delta b_2 \tag{14}$$

$$d_{d2} = ah - p_{d2} + \gamma p_{r2} + \eta t_2 \tag{15}$$

The manufacturer profit function is

$$\Pi_2^M = w_{r2} d_{r2} + p_{d2} d_{d2} - \frac{1}{2} k_\tau t_2^2 \tag{16}$$

Correspondingly, the profit function of the retailer is

$$\Pi_2^S = \left(p_{r2} - w_{r2}\right) d_{r2} - \frac{1}{2} k_b b_2^2 \tag{17}$$

**Theorem 2** *The optimal decisions of the supply chain members under the manufacturer's online direct sales dual-channel model are respectively.*

$$w_2^* = \frac{a(2h\gamma - h + 1)}{2\left(1-2\gamma^2\right)} + \frac{(1+2\gamma)\eta t_2}{2\left(1-2\gamma^2\right)} + \frac{\delta b_2}{2\left(1-2\gamma^2\right)} \tag{18}$$

$$p_{r2}^* = \frac{a\left(2h\gamma^2 - 2\gamma^2 + 4h\gamma - 3h + 3\right)}{4\left(1-2\gamma^2\right)} + \frac{\left(3 + 4\gamma - 2\gamma^2\right)\eta t_2}{4\left(1-2\gamma^2\right)} + \frac{\left(3-2\gamma^2\right)\delta b_2}{4\left(1-2\gamma^2\right)} \tag{19}$$

$$p_{d2}^* = \frac{a(h + \gamma - h\gamma)}{1-2\gamma^2} + \frac{(1+\gamma)\eta t_2}{1-2\gamma^2} + \frac{\gamma \delta b_2}{1-2\gamma^2} \tag{20}$$

$$d_{r2}^* = \frac{a(1-h)}{4} + \frac{\left(\eta t_2 + \delta b_2\right)}{4} \tag{21}$$

$$d_{d2}^* = \frac{a(-h\gamma + 2h + \gamma)}{4} + \frac{(2+\gamma)\eta t_2}{4} + \frac{\gamma \delta b_2}{4} \tag{22}$$

$$\begin{aligned}\Pi_2^{M*} = {} & \frac{a^2\left(2h^2\gamma^2 - 8h^2\gamma - 4h\gamma^2 + 4h^2 + 2\gamma^2 + 8h\gamma - 2h + 1\right)}{8\left(1-2\gamma^2\right)} + \frac{a\left(-2h\gamma^2 + 2\gamma^2 + 3h + 4\gamma + 1\right)\eta t_2}{4\left(1-2\gamma^2\right)} \\ & + \frac{a\left(-2h\gamma^2 + 2\gamma^2 + 3h + 4\gamma + 1\right)\delta b_2}{4\left(1-2\gamma^2\right)} + \frac{\left(2\gamma^2 + 4\gamma + 1\right)\eta t_2 \delta b_2}{4\left(1-2\gamma^2\right)} \\ & + \frac{\left(2\gamma^2 + 8\gamma + 5\right)\left(\eta t_2\right)^2}{8\left(1-2\gamma^2\right)} + \frac{\left(2\gamma^2 + 1\right)\left(\delta b_2\right)^2}{8\left(1-2\gamma^2\right)} - \frac{1}{2} k_\tau t_2^2\end{aligned} \tag{23}$$

$$\Pi_2^{S*} = \frac{a^2\left(1-h^2\right)}{16} + \frac{a(1-h)\left(\eta t_2 + \delta b_2\right)}{8} + \frac{\left(\eta t_2 + \delta b_2\right)^2}{16} - \frac{1}{2} k_b b_2^2 \tag{24}$$

***Proof*** See Appendix.

**Proposition 4** (1) $\frac{\partial t_2^*}{\partial \eta} > 0$, $\frac{\partial t_2^*}{\partial \delta} > 0$; (2) $\frac{\partial w_2^*}{\partial \eta} > 0$, $\frac{\partial p_{r2}^*}{\partial \eta} > 0$, $\frac{\partial p_{d2}^*}{\partial \eta} > 0$; (3) *the existence of an abatement cost factor threshold* $k_\tau' = \frac{\left(2\gamma^2+8\gamma+5\right)\eta^2}{4\left(1-2\gamma^2\right)}$, *when* $k_\tau > k_\tau'$, *there exists an optimal amount of emission reduction* $t_2^* = \frac{\left(2\gamma^2+4\gamma+1\right)\eta\left(a+\delta b_2\right)+\left(3-2\gamma^2\right)h\eta a}{4k_\tau\left(1-2\gamma^2\right)-\left(2\gamma^2+8\gamma+5\right)\eta^2}$, *such that the manufacturer's profit* $\Pi_2^M$ *reaches the optimal value*; (3) $\frac{\partial d_{r2}^*}{\partial \eta} > 0$, $\frac{\partial d_{d2}^*}{\partial \eta} > 0$, $\frac{\partial \Pi_2^{S*}}{\partial t_2} > 0$, $\frac{\partial^2 \Pi_2^{S*}}{\partial t_2^2} > 0$.

***Proof:*** (1) $\frac{\partial t_2^*}{\partial \eta} = \frac{\left(2\gamma^2+4\gamma+1\right)\left(a+\delta b_2\right)+\left(3-2\gamma^2\right)ha}{4k_\tau\left(1-2\gamma^2\right)-\left(2\gamma^2+8\gamma+5\right)\eta^2} + \frac{\left[\left(2\gamma^2+4\gamma+1\right)\eta\left(a+\delta b_2\right)+\left(3-2\gamma^2\right)h\eta a\right]2\eta\left(2\gamma^2+8\gamma+5\right)}{\left[4k_\tau\left(1-2\gamma^2\right)-\left(2\gamma^2+8\gamma+5\right)\eta^2\right]^2} > 0$, $\frac{\partial w_2^*}{\partial \eta} = \frac{\partial w_2^*}{\partial t_2} * \frac{\partial t_2}{\partial \eta} = \frac{(1+2\gamma)\eta}{2\left(1-2\gamma^2\right)} \frac{\partial t_2}{\partial \eta} > 0$, and the same reason can be proven $\frac{\partial p_{r2}^*}{\partial \eta} > 0$, $\frac{\partial p_{d2}^*}{\partial \eta} > 0$; (2) $\frac{\partial \Pi_2^{M*}}{\partial t_2} = \frac{\left(2\gamma^2+8\gamma+5\right)\eta}{4\left(1-2\gamma^2\right)}\eta t_2 + \frac{a\left(-2h\gamma^2+2\gamma^2+3h+4\gamma+1\right)}{4\left(1-2\gamma^2\right)}\eta + \frac{\left(2\gamma^2+4\gamma+1\right)\eta}{4\left(1-2\gamma^2\right)}\delta b_2 - k_\tau t_2$, $\frac{\partial^2 \Pi_2^{M*}}{\partial t_2^2} = \frac{\left(2\gamma^2+8\gamma+5\right)\eta^2}{4\left(1-2\gamma^2\right)} - k_\tau$, when $\frac{\partial^2 \Pi_2^{M*}}{\partial t_2^2} < 0$ and $\frac{\partial \Pi_2^{M*}}{\partial t_2} = 0$, there exists an optimal amount of emission reduction $t_2^*$, such that the manufacturer's profit $\Pi_2^{M*}$ reaches the optimal value; (3) $\frac{\partial d_{r2}^*}{\partial \eta} = \frac{1}{4}t_2 > 0$, $\frac{\partial d_{d2}^*}{\partial \eta} = \frac{2+\gamma}{4}t_2 > 0$, $\frac{\partial \Pi_2^{S*}}{\partial t_2} = \frac{\eta}{2}\left(a\frac{1-h}{4} + \frac{1}{4}\left(\eta t_2 + \delta b_2\right)\right) > 0$, $\frac{\partial^2 \Pi_2^{S*}}{\partial t_2^2} = \frac{\eta^2}{8} > 0$.

From Proposition 4, it can be seen that under the manufacturer's online direct sales dual-channel model, both manufacturer dual-channel price and retailer selling price are positively correlated with consumer low-carbon preferences. Indicating that the higher the consumers' low-carbon preferences, both the manufacturer and retailer will adopt higher selling prices to obtain higher profits. When $k_\tau > k_\tau'$, the manufacturer has the best emission reduction ${t_2}^*$. Meanwhile, the emission reduction investment will always improve dual-channel demand and retailer profit, and the improvement to demand is linear. And the improvement in retailer profit increases with the increase of emission reduction investment, which is a concave function.

**Proposition 5** (1) $\frac{\partial b_2^*}{\partial \delta} > 0$, $\frac{\partial b_2^*}{\partial \eta} > 0$; (2) $\frac{\partial w_2^*}{\partial \delta} > 0$, $\frac{\partial p_{r2}^*}{\partial \delta} > 0$, $\frac{\partial p_{d2}^*}{\partial \delta} > 0$; (3) $\frac{\partial \Pi_2^M}{\partial b_2} > 0$, $\frac{\partial^2 \Pi_2^M}{\partial b_2^2} > 0$; (4) *the existence of a blockchain cost coefficient threshold* $k_b' = \frac{\delta^2}{8}$, *when* $k_b > k_b'$, *there exists an optimal amount of blockchain investment* $b_2^* = \frac{a(1-h)+\eta t_2}{4\left(2\frac{k_b}{\delta}-\delta\right)}$ *such that the retailer's profit* $\Pi_2^S$ *reaches the optimal value.*

***Proof:*** The proof process is the same as that of Proposition 4.

From Proposition 5, the impact of blockchain investment level on pricing and demand is influenced by the price sensitivity coefficient γ, which has a similar trend to the impact of abatement investment. By increasing the level of blockchain investment, it will increase the selling price and demand and enhance the manufacturer's profit. Meanwhile, when $k_b > k_b'$, there exists an optimal blockchain investment level ${b_2}^*$ for the retailer, which makes the retailer's profit optimal.

## Dual-channel model of third-party e-commerce distribution (Model C)

In the dual-channel model of third-party e-commerce distribution, there exist three members: manufacturers, traditional retailers, and third-party e-commerce. Low-carbon products are sold through offline and online channels, respectively. In the decentralized decision-making model, manufacturers, traditional retailers, and third-party e-merchants make decisions based on the principle of maximizing their respective profits. In the game process, firstly, the supply price $w_{d3}$, $w_{r3}$ and carbon reduction rate $t_3$ for online and offline channels are decided by the manufacturer; then, the offline sales price $p_{r3}$ is set by the traditional retailer based on the wholesale price $w_{r3}$ given by the manufacturer, and the offline sales price $p_{d3}$ is set by the third-party e-merchant based on the wholesale price $w_{d3}$ given by the manufacturer, and the retailer and the third-party e-merchant make separate decisions that do not affect each other. Where the retailer and the third-party e-merchant decide their respective blockchain investment levels $b_{r3}$ and $b_{d3}$, respectively, which leads to the decision profit function of the supply chain under the dual channel of third-party e-merchant distribution (Yang et al. 2018).

The demand function is

$$d_{r3} = a(1-h) - p_{r3} + \gamma p_{d3} + \eta t_3 + \delta b_{r3} \tag{25}$$

$$d_{d3} = ah - p_{d3} + \gamma p_{r3} + \eta t_3 + \delta b_{d3} \tag{26}$$

The manufacturer profit function is

$$\Pi_3^M = w_{r3}d_{r3} + w_{d3}d_{d3} - \frac{1}{2}k_\tau t_3^2 \tag{27}$$

Correspondingly, the profit function for a traditional retailer is

$$\Pi_3^r = \left(p_{r3} - w_{r3}\right)d_{r3} - \frac{1}{2}k_b b_{r3}^2 \tag{28}$$

The profit function of the online retailer is

$$\Pi_3^d = \left(p_{d3} - w_{d3}\right)d_{d3} - \frac{1}{2}k_b b_{d3}^2 \tag{29}$$

**Theorem 3** *The optimal decisions of the supply chain members under the dual-channel model of online distribution for retailers are respectively.*

$$w_{r3}^* = \frac{a(1-h+h\gamma)}{2\left(1-\gamma^2\right)} + \frac{\eta t_3}{2(1-\gamma)} + \frac{\delta b_{r3}}{2\left(1-\gamma^2\right)} + \frac{\gamma\delta b_{d3}}{2\left(1-\gamma^2\right)} \tag{30}$$

$$w_{d3}^* = \frac{a(\gamma+h-h\gamma)}{2\left(1-\gamma^2\right)} + \frac{\eta t_3}{2(1-\gamma)} + \frac{\gamma\delta b_{r3}}{2\left(1-\gamma^2\right)} + \frac{\delta b_{d3}}{2\left(1-\gamma^2\right)} \tag{31}$$

$$\begin{aligned} p_{r3}^* = {} & a\left(\frac{3-2\gamma}{4(2-\gamma)(1-\gamma)} + \frac{(1-2h)(3+2\gamma)}{4(2+\gamma)(1+\gamma)}\right) + \frac{(3-2\gamma)\eta t_3}{2(2-\gamma)(1-\gamma)} \\ & + \frac{3\left(2-\gamma^2\right)\delta b_{r3}}{2\left(4-\gamma^2\right)\left(1-\gamma^2\right)} + \frac{\left(-2\gamma^3+5\gamma\right)\delta b_{d3}}{2\left(4-\gamma^2\right)\left(1-\gamma^2\right)} \end{aligned} \tag{32}$$

$$\begin{aligned} p_{d3}^* = {} & a\left(\frac{3-2\gamma}{4(2-\gamma)(1-\gamma)} - \frac{(1-2h)(3+2\gamma)}{4(2+\gamma)(1+\gamma)}\right) + \frac{(3-2\gamma)\eta t_3}{2(2-\gamma)(1-\gamma)} \\ & + \frac{\left(-2\gamma^3+5\gamma\right)\delta b_{r3}}{2\left(4-\gamma^2\right)\left(1-\gamma^2\right)} + \frac{3\left(2-\gamma^2\right)\delta b_{d3}}{2\left(4-\gamma^2\right)\left(1-\gamma^2\right)} \end{aligned} \tag{33}$$

$$d_{r3}^* = \frac{a(h\gamma-2h+2)}{2\left(4-\gamma^2\right)} + \frac{\eta t_3}{2(2-\gamma)} + \frac{\gamma\delta b_{r3}}{2\left(4-\gamma^2\right)} + \frac{\delta b_{d3}}{\left(4-\gamma^2\right)} \tag{34}$$

$$d_{d3}^* = \frac{a(-h\gamma+2h+\gamma)}{2\left(4-\gamma^2\right)} + \frac{\eta t_3}{2(2-\gamma)} + \frac{\delta b_{r3}}{\left(4-\gamma^2\right)} + \frac{\gamma\delta b_{d3}}{2\left(4-\gamma^2\right)} \tag{35}$$

$$\begin{aligned} \Pi_3^{M*} = {} & \frac{a^2(\gamma^2-2h(1-h)(2-\gamma)(1-\gamma)+2)}{4(4-\gamma^2)(1-\gamma^2)} + \frac{a(2\eta t_3+\delta b_{r3}+\delta b_{d3})}{4(2-\gamma)(1-\gamma)} \\ & + \frac{\eta t_3(\eta t_3+\delta b_{r3}+\delta b_{d3})}{2(2-\gamma)(1-\gamma)} + \frac{2(2+\gamma^2)\delta^2 b_{r3}b_{d3}+3\gamma\delta^2({b_{r3}}^2+{b_{d3}}^2)}{4(4-\gamma^2)(1-\gamma^2)} - \frac{1}{2}k_\tau t_3^2 \end{aligned} \tag{36}$$

$$\begin{aligned} \Pi_3^{r*} = {} & \frac{(a(h\gamma-2h+2)+(2+\gamma)\eta t_3)(2+\gamma)\delta(b_{r3}+b_{d3})}{4(4-\gamma^2)^2} \\ & + \frac{(a(h\gamma-2h+2)+(2+\gamma)\eta t_3)^2}{4(4-\gamma^2)^2} \\ & + \frac{(2\delta b_{r3}+\gamma\delta b_{d3})(\gamma\delta b_{r3}+2\delta b_{d3})}{4(4-\gamma^2)^2} - \frac{1}{2}k_b b_{r3}^2 \end{aligned} \tag{37}$$

$$\begin{aligned} \Pi_3^{d*} = {} & \frac{(a(-h\gamma+2h+\gamma)+(2+\gamma)\eta t_3)(2+\gamma)\delta(b_{r3}+b_{d3})}{4(4-\gamma^2)^2} \\ & + \frac{(a(-h\gamma+2h+\gamma)+(2+\gamma)\eta t_3)^2}{4(4-\gamma^2)^2} \\ & + \frac{(\gamma\delta b_{r3}+2\delta b_{d3})(2\delta b_{r3}+\gamma\delta b_{d3})}{4(4-\gamma^2)^2} - \frac{1}{2}k_b b_{d3}^2 \end{aligned} \tag{38}$$

**Proposition 6** (1) *There is* $h' = \frac{1}{2} - \frac{\delta\Delta b_3}{a}$, *when* $h < h'$, $w_{r3}^* > w_{d3}^*$, $p_{r3}^* > p_{d3}^*$, *when* $h' < h < 1$, $w_{r3}^* < w_{d3}^*$, $p_{r3}^* < p_{d3}^*$; *there is* $h'' = \frac{1}{2} + \frac{\delta\Delta b_3}{a}$, *when* $h < h''$, $d_{r3}^* > d_{d3}^*$, *when* $h'' < h < 1$, $d_{r3}^* < d_{d3}^*$; (2) $\frac{\partial\Delta w_3^*}{\partial h} < 0$, $\frac{\partial\Delta d_3^*}{\partial h} < 0$, $\frac{\partial\Delta p_3^*}{\partial h} < 0$; (3) *when* $h < \frac{1}{2}$, $\frac{\partial\Delta w_3^*}{\partial\gamma} < 0$, $\frac{\partial\Delta p_3^*}{\partial\gamma} < 0$, *when* $h > \frac{1}{2}$, $\frac{\partial\Delta w_3^*}{\partial\gamma} > 0$, $\frac{\partial\Delta p_3^*}{\partial\gamma} > 0$.

***Proof:*** (1) $w_{r3}^* - w_{d3}^* = \Delta w_3^* = \frac{1}{2(1+\gamma)}\left(a(1-2h)+\delta\Delta b_3\right)$, $p_{r3}^* - p_{d3}^* = \Delta p_3^* = \frac{3+2\gamma}{2(2+\gamma)(1+\gamma)}\left(a(1-2h)+\delta\Delta b_3\right)$, $d_{r3}^* - d_{d3}^* = \Delta d_3^* = \frac{1}{2(2+\gamma)}\left(a(1-2h)-\delta\Delta b_3\right)$, $\Delta b_3 = b_{r3} - b_{d3}$; (2) $\frac{\partial\Delta w_3^*}{\partial h} = -\frac{a}{1+\gamma} < 0$, $\frac{\partial\Delta d_3^*}{\partial h} = -\frac{a}{2+\gamma} < 0$,

$\frac{\partial \Delta p_3^*}{\partial h} = -\frac{a(3+2\gamma)}{(2+\gamma)(1+\gamma)} < 0$; (3) $\frac{\partial \Delta w_3^*}{\partial \gamma} = -\frac{a(1-2h)}{2(1+\gamma)^2}$, $\frac{\partial \Delta p_3^*}{\partial \gamma} = -\frac{a(1-2h)}{2(2+\gamma)^2}$, when $h < \frac{1}{2}$, $\frac{\partial \Delta w_3^*}{\partial \gamma} < 0$, $\frac{\partial \Delta p_3^*}{\partial \gamma} < 0$, when $h > \frac{1}{2}$, $\frac{\partial \Delta w_3^*}{\partial \gamma} > 0$, $\frac{\partial \Delta p_3^*}{\partial \gamma} > 0$.

From Proposition 6, it can be seen that under the dual-channel model of third-party e-commerce distribution, when $0 < h < h'$, consumers prefer the traditional retail channel, and the manufacturer's retail channel pricing and the traditional retailer selling price are higher than the third-party e-commerce. When $h' < h < 1$, the preference of the third-party e-commerce channel is higher, indicating that consumer preference has a dominant role in inter-channel pricing. Meanwhile, when $0 < h < h''$, the demand of retailers is higher than the demand of third-party e-commerce channels. Since the low-carbon promotion is separately undertaken by retailers and third-party e-merchants, respectively, the inter-channel pricing and demand are influenced by the difference in blockchain investment $\Delta b_3$, and the party with higher blockchain investment gains higher pricing power. The $\Delta b_3$ has an opposite effect on pricing and demand. This is in line with the reality that it is difficult to achieve both high prices and high demand under either party's channel. And the trends of the differential affected by $h$, $r$ are similar to that under the two-channel model for retailers.

**Proposition 7** (1) *When* $k_b > \frac{(4+\gamma^2)+4\gamma\delta}{4(4-\gamma^2)}\delta^2$, $\frac{\partial t_3^*}{\partial \eta} > 0$, $\frac{\partial t_3^*}{\partial \delta} > 0$; (2) $\frac{\partial w_{d3}^*}{\partial \eta} > 0$, $\frac{\partial w_{r3}^*}{\partial \eta} > 0$, $\frac{\partial p_{r3}^*}{\partial \eta} > 0$, $\frac{\partial p_{d3}^*}{\partial \eta} > 0$; (3) *the existence of an abatement cost factor threshold* $k_\tau' = \frac{\eta^2}{4(1-\gamma)}$, *when* $k_\tau > k_\tau'$, *there exists an optimal amount of carbon emission* $t_3^* = \frac{a\eta+(b_{r3}+b_{d3})\delta\eta}{2(k_\tau(1-\gamma)(2-\gamma)-\eta^2)}$ *such that the manufacturer's profit* $\Pi_3^M$ *reaches the optimal value*; (4) $\frac{\partial \Pi_3^{S*}}{\partial t_3} > 0$, $\frac{\partial^2 \Pi_3^{S*}}{\partial t_3^2} > 0$.

***Proof:*** The proof procedure is the same as the proof of Proposition 2.

From Proposition 7, the abatement sensitivity coefficient is positively correlated with manufacturer dual-channel pricing, retailer and third-party e-commerce selling prices, and abatement investment and blockchain investment levels under the dual-channel model of third-party e-commerce distribution. The emission reduction investment $t$ is positively correlated with both pricing and demand. When $k_\tau > k_\tau'$, there exists an optimal emission reduction $t_3{}^*$ for the manufacturer, which makes the manufacturer profit $\Pi_3^M$ reach the optimal value. Meanwhile, as the emission reduction investment increases, the retailer's profit increases. This is due to the fact that retailers are the beneficiaries of emission reduction, as they do not bear the cost of emission reduction, so the emission reduction investment shows a linear positive correlation with retailer profit.

**Proposition 8** (1) $\frac{\partial b_{r3}^*}{\partial \delta} > 0$, $\frac{\partial b_{d3}^*}{\partial \delta} > 0$; (2) $\frac{\partial w_{r3}^*}{\partial \delta} > 0$, $\frac{\partial w_{d3}^*}{\partial \delta} > 0$, $\frac{\partial p_{r3}^*}{\partial \delta} > 0$, $\frac{\partial p_{d3}^*}{\partial \delta} > 0$; (3) $\frac{\partial \Pi_3^M}{\partial b_{r3}} > 0$, $\frac{\partial^2 \Pi_3^M}{\partial b_{r3}^2} > 0$, $\frac{\partial \Pi_3^M}{\partial b_{d3}} > 0$, $\frac{\partial^2 \Pi_3^M}{\partial b_{d3}^2} > 0$; (4) *the existence of a blockchain cost coefficient threshold* $k_b = \frac{\gamma\delta^2}{(4-\gamma^2)^2}$, *when* $k_b > k_b'$, *there are exist optimal blockchain investment levels* $b_{r3}^* = \frac{a(h\gamma-2h+2)(2+\gamma)+(2+\gamma)^2\eta t_3}{4\left(\frac{k_b}{\delta}(4-\gamma^2)^2-4\gamma\delta-(4+\gamma^2)\delta\right)}$ *for retailers and* $b_{d3}^* = \frac{a(-h\gamma+2h+\gamma)(2+\gamma)+(2+\gamma)^2\eta t_3}{4\left(\frac{k_b}{\delta}(4-\gamma^2)^2-4\gamma\delta-(4+\gamma^2)\delta\right)}$ *for third-party e-commerce such that the snacker profit* $\Pi_3^r$ *and the third-party e-commerce profit* $\Pi_3^d$ *reach optimal values, respectively.*

***Proof*** (1) It is similar to proposition 4; (2) $\frac{\partial w_{r3}^*}{\partial \delta} = \frac{b_{r3}+\gamma b_{d3}}{2(1-\gamma^2)} > 0$, $\frac{\partial p_{r3}^*}{\partial \delta} = \frac{3(2-\gamma^2)b_{r3}+(-2\gamma^3+5\gamma)b_{d3}}{2(4-\gamma^2)(1-\gamma^2)} > 0$, and the same can be proven $\frac{\partial w_{d3}^*}{\partial \delta} > 0$, $\frac{\partial p_{d3}^*}{\partial \delta} > 0$; (3) $\frac{\partial \Pi_3^M}{\partial b_{r3}} = \frac{(a+2\eta t_3)\delta}{4(2-\gamma)(1-\gamma)} + \frac{(3\gamma\delta b_{r3}+(2+\gamma^2)\delta b_{d3})\delta}{2(4-\gamma^2)(1-\gamma^2)} > 0$, and the same can be proven $\frac{\partial \Pi_3^M}{\partial b_{d3}} > 0$, $\frac{\partial^2 \Pi_3^M}{\partial b_{r3}^2} = \frac{\partial^2 \Pi_3^M}{\partial b_{d3}^2} = \frac{3\gamma\delta^2}{2(4-\gamma^2)(1-\gamma^2)} > 0$; (4) $\frac{\partial \Pi_3^r}{\partial b_{r3}} = \frac{\delta a(h\gamma^2+2\gamma-4h+4)}{4(4-\gamma^2)^2} + \frac{4\gamma\delta^2 b_{r3}+(4+\gamma)^2\delta^2 b_{d3}}{4(4-\gamma^2)^2} + \frac{\delta(2+\gamma)^2\eta t_3}{4(4-\gamma^2)^2} - k_b b_{r3}$, $\frac{\partial^2 \Pi_3^r}{\partial b_{d3}^2} = \frac{\gamma\delta^2}{(4-\gamma^2)^2} - k_b$, $\frac{\partial \Pi_3^d}{\partial b_{d3}} = \frac{\delta a(-h\gamma^2+\gamma^2+4h+2\gamma)}{4(4-\gamma^2)^2} + \frac{(4+\gamma)^2\delta^2 b_{r3}+4\gamma\delta^2 b_{d3}}{4(4-\gamma^2)^2} + \frac{\delta(2+\gamma)^2\eta t_3}{4(4-\gamma^2)^2} - k_b b_{d3}$ $\frac{\partial^2 \Pi_3^d}{\partial b_{d3}^2} = \frac{\gamma\delta^2}{(4-\gamma^2)^2} - k_b$, when $\frac{\partial^2 \Pi_3^M}{\partial b_{r3}^2} = \frac{\partial^2 \Pi_3^M}{\partial b_{d3}^2} < 0$, $\frac{\partial \Pi_3^M}{\partial b_{r3}} = 0$, $\frac{\partial \Pi_3^M}{\partial b_{d3}} = 0$, the snacker profit $\Pi_3^r$ and the third-party e-commerce profit $\Pi_3^d$ reach optimal values, respectively.

Proposition 8 shows that under the dual-channel model of third-party e-commerce distribution, blockchain investment levels $b_{r3}$ and $b_{d3}$ for both channels are positively correlated with the supply price, pricing, and demand for the product, and both increase the manufacturer's profit. However, the degree of impact on decisions under different channels differs, with the blockchain investment of the third-party e-commerce channel having a higher degree of impact on its own channel than the other channel, and the same for the retailer channel. When $k_b > k_b'$, there exist optimal blockchain investment levels $b_{r3}{}^*$ and $b_{d3}{}^*$, respectively, which makes the traditional retailer profit and third-party e-commerce profit reach the optimal value.

## Algorithm analysis

The previous section analyzed the impact of low-carbon emission reduction and blockchain investment on the optimal decision of the supply chain under three different dual-channel models. Based on this, this section uses numerical simulations based on MATLAB 2018b platform to further verify the rationality and correctness of the above conclusions, taking the core parameters of emission reduction investment, blockchain investment, and inter-channel as the influencing factors. The simulation results are obtained by programming and calculating the model formula above. In conducting the analysis, the values of fixed parameters are set as follows in order to simplify the arithmetic example and conform to the feasible region: $a = 150$, $\eta = 1$, $\delta = 1$, $b = 10$, $k_\tau = 10$, $k_b = 10$ (Wang et al. 2018; Yang et al. 2018).

## Impact of emission reduction investment and blockchain investment on supply chain profit

In analyzing the impact of emission reduction investment $t$ and blockchain investment $b$, given the dual-channel impact parameters $h, \gamma$, such that $h = 0.4$, $\gamma = 0.2$, the impact of $t$ and $b$ changes on the pricing and optimal profit of supply chain members is specifically analyzed.

(1) Retailers' dual-channel arithmetic analysis.

As can be seen from Fig. 2, under the retailer dual-channel model, the investment of emission reduction technology $t$ and blockchain technology $b$ will improve the profit of members by increasing the selling price and demand for products (Liu et al. 2021b). However, considering the impact of abatement and blockchain costs, the gaining effect on the cost investment side and the beneficiary side is different. The beneficiary side, which is in a ride-along role, experiences a nearly linear increase in profits as the level of investment increases. The investment side, on the other hand, is influenced by the investment cost, and the profit shows a parabolic trend of convex function with a maximum profit point. The impact of $t$ and $b$ on supply chain members has the same trend.

Figure 3 shows the trend of the interaction impact of $t$ and $b$ on the profits of manufacturers and retailers. It can be found that the decision process is always dominated by the manufacturer, while the interaction has a higher degree and complexity of impact on the manufacturer's profit than on the retailer's profit. Analysis of the overall trend shows that when the level of blockchain investment $b$ is low, the market for low-carbon products is depressed. At this time, increasing the investment in emission reduction technology $t$ has a limited impact on retailers' profits while significantly increasing manufacturers' cost investment. However, as the blockchain investment $b$ increases, it can significantly improve the effectiveness of the manufacturer's emission reduction investment and make the overall profit of the system increase rapidly, while the technical cost borne by the retailer is maintained at a lower profit level. A similar conclusion is also obtained in the study of Wu et al. (2021): "When the low-carbon market is in a downturn, improving consumers' low-carbon awareness will help promote low-carbon operations." Therefore, retailers should increase blockchain investment in the dual-channel model while a reasonable investment in emission reduction, which can achieve the optimal profit of the supply chain system. However, at this time, the difference in profits between supply and sales is large. And better win–win cooperation can be achieved by sharing part of the blockchain investment costs of retailers in the subsequent study. Zhang and Yu (2021) and Ghosh et al. (2020) have carried out similar research on emission reduction and achieved supply chain coordination.

(2) Manufacturer's online direct marketing dual-channel arithmetic analysis.

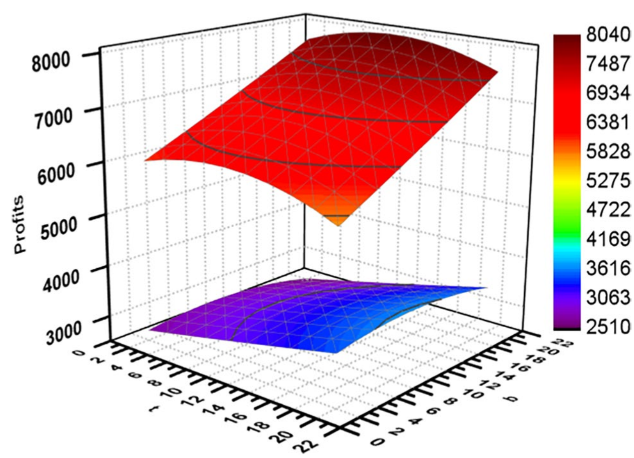
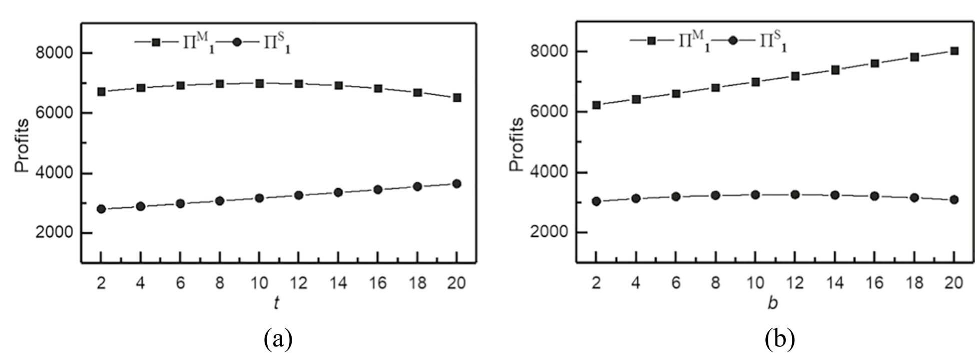



**Fig. 3** The interactive impact of emission reduction rates and blockchain investment on profits

**Fig. 2** Impact of emission reduction rates and blockchain investment on profits (**a**) Impact of $t$ on pricing decisions; (**b**) Impact of $b$ on pricing decisions



As can be seen from Fig. 4, when the dual-channel model of online direct sales by the manufacturer is adopted, the investment of $t$ is more flexible in regulating the online channel, while the investment of $b$ focuses on influencing the traditional channel marketing. The online channel is the main way for the manufacturer's market regulation. And when the product abatement investment $t$ is low, the manufacturer will drive the traditional channel sales by reducing the selling price of the online channel and conducting low-price marketing to stimulate market demand. Comparing the profits of supply chain members shows that the manufacturer is responsible for both the supply of products in traditional channels and also undertakes sales in online direct sales channels, and the benefit of emission reduction is more obvious. At the early stage of low-carbon investment, profits increase significantly, and the trend of growth slows down in the later stage of investment due to the impact of costs. The retailer, on the other hand, is relatively passive in the supply chain and suffers from limited gains in emission reduction technology while bearing the full cost of blockchain investments (Xin et al. 2019).

As shown in Fig. 5, by analyzing the trend of the impact of $t$ and $b$ interaction on manufacturer and retailer profits, it can be seen that high emissions reduction investments come at the expense of some retailers' profits, and the gains to manufacturers' profits are even more pronounced. This also leads to the fact that manufacturers are more inclined to invest more in abatement technology in the dual-channel model of online direct sales by manufacturers, which is conducive to low-carbon product promotion. And this trend is more obvious with high blockchain investment. However, with low-carbon investment, it also leads to an increase in the profit differential between manufacturers and retailers, which is not conducive to long-term healthy cooperation between them. This is similar to the findings of Ghosh et al. (2020), who argue that "when the compatibility of products in the online channel is high, increasing the online channel can be accepted by the manufacturer and is detrimental to the retailer's entire supply chain." Therefore, under this model, a higher blockchain investment and reasonable carbon emission reduction investment are the best decisions.

(3) Third-party e-commerce distribution dual-channel arithmetic analysis.

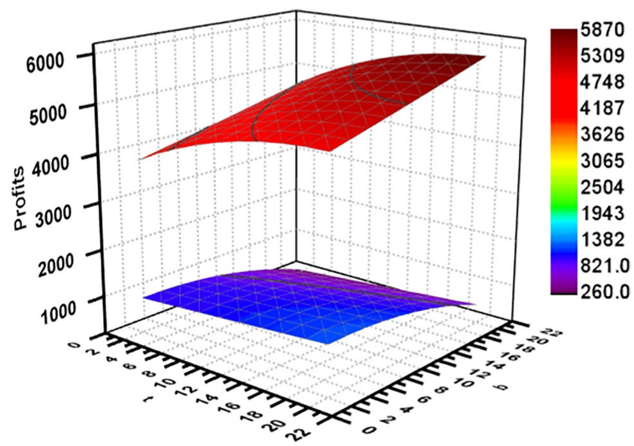



**Fig. 5** Interactive impact of emission reduction rates and blockchain investment on profits

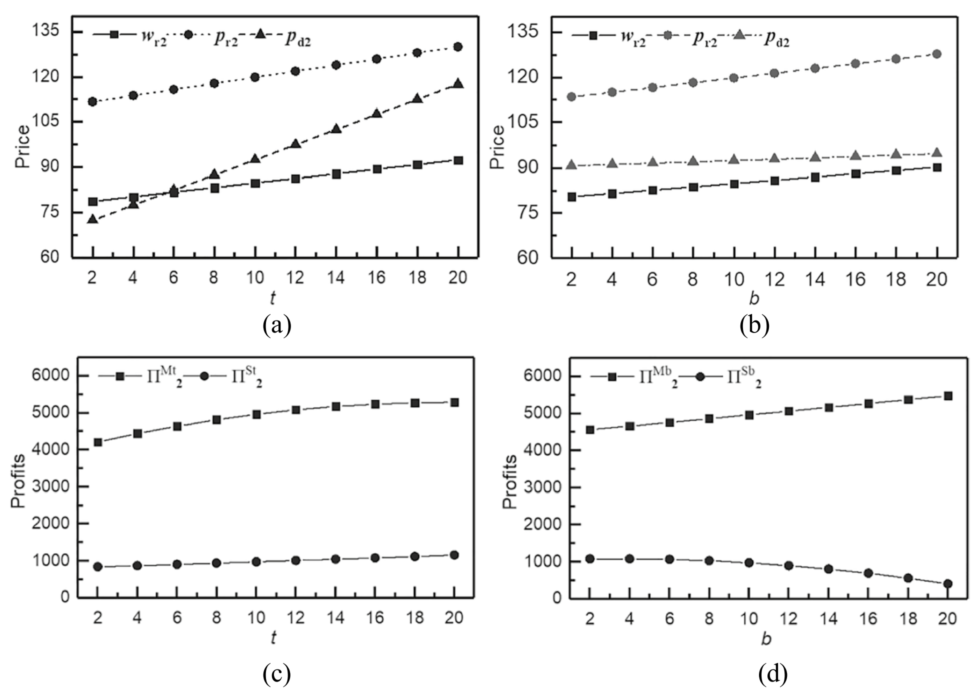



**Fig. 4** Impact of abatement rates and blockchain investment on manufacturers' dual-channel decisions (**a**) Impact of $t$ on pricing decisions; (**b**) Impact of $b$ on pricing decisions; (**c**) Impact of $t$ on profits; (**d**) Impact of $b$ on profits

As can be seen from Fig. 6, under the dual-channel model of third-party e-commerce distribution, the impact of $t$ and $b$ on members' profits is similar to that of the dual-channel model of retailers. As the investment increases, the manufacturer, as the low-carbon investment, is affected by the investment cost and has a parabolic increasing trend with a peak profit point. Comparing the three types of models at the same time, it is found that the ratio of the manufacturer's technology benefit to cost investment influences the peak region. As the beneficiaries, retailers and third-party e-commerce companies have increased profits.

Figure 7 shows the trend of the impact of $t$ and $b$ interactions on members' profits. It can be seen that the interaction has the same trend of impact on retailers and third-party e-merchants, and the channel share $h$ affects the difference between their profits. When the market is low, manufacturers' higher-cost investment greatly reduces their own profits and is harmful to the overall supply chain revenue. In contrast, the incentive of blockchain investments to market demand can significantly boost overall profits (Liu et al. 2021b). The enhancement effect is more obvious when manufacturers have high emission reduction investments. Besides, blockchain investment costs are shared by retailers and third-party e-commerce, and the loss of profit to the selling side is not obvious. Therefore, the third-party e-commerce distribution should invest in maximizing blockchain technology while making appropriate emission reduction investments to make the supply chain system achieve optimal profits.

## Impact of dual-channel model on enterprise pricing and supply chain profit

The following section analyzes the impact of dual-channel parameters on supply chain profit, and the analysis process takes the optimal emission reduction and the optimal blockchain investment level for $t$ and $b$, respectively, and specifically analyzes the impact of the change of the online channel share $h$ on the pricing and optimal profit of supply chain members.

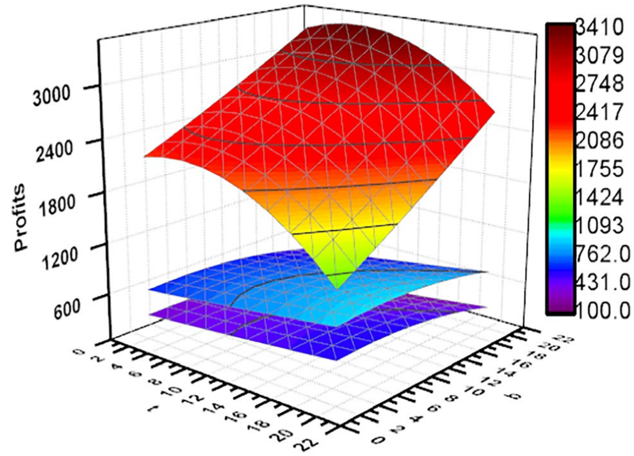



**Fig. 7** Interaction of emission reduction rates and blockchain investment on profits

(1) Analysis of retailer dual-channel calculations.

As shown in Fig. 8, when the dual-channel model of retailers is adopted, the online channel share $h$ indirectly affects the channel pricing by influencing the channel demand. Analyzed from the member profit perspective, the different $h$ affects the revenue between the two channels of the retailer. When the inter-channel share difference $\Delta h$ is large, there is healthy competition between the online and offline channels and the total profit of the retailer increases. When the offline channel is dominant, the supply chain is still dominated by the traditional channel and the online channel will attract consumers by reducing the selling price. The increase of $h$ will reduce the demand and revenue of traditional channels, resulting in lower profits for manufacturers and lower profits for the supply chain as a whole.

(2) Dual-channel online direct marketing for manufacturer.

As shown in Fig. 9, under the manufacturer's online direct sales dual channel, the manufacturer has both the traditional channel and the online direct sales channel. Therefore, the

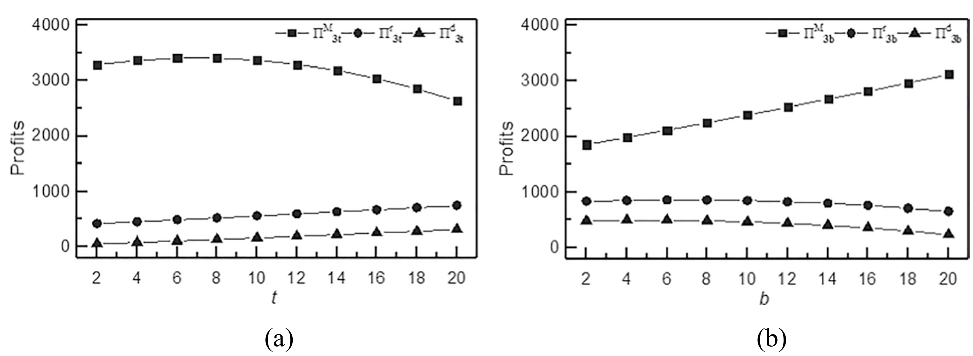



**Fig. 6** Impact of emission reduction rates and blockchain investment on third-party e-commerce distribution decisions (**a**) Impact of $t$ on profits; (**b**) Impact of $b$ on profits

increase of $h$ is the most significant profit enhancement for the manufacturer. When $h$ is low, the online direct sales channel attracts consumers by lowering the selling price, which will even be lower than the supply price of the traditional channel. When $h$ is high, the online channel dominates and the online direct sales revenue takes up almost all of the manufacturer's profit. At this time, the total profit level of the system is higher, but the traditional channel market is negative, and retailers' profits are damaged, forming a monopoly situation for the manufacturer.

(3) Retailer online distribution dual channel.

As shown in Fig. 10, there is a significant symmetry in the product pricing and profit distribution of supply chain members with the variation of $h$, under the dual channels of retailer online distribution. The change in manufacturer profits reflects the level of aggregate demand, and healthy competition is formed between the dual channels when the $\Delta h$ is high. Traditional retailers and third-party e-commerce profits are directly affected by their respective market shares.

## Comparative analysis of supply chain decisions under three dual-channel models

(1) Analysis of enterprise profits under three dual-channel models.

The following section analyzes the comparison of profit levels of the three dual-channel modes under different technological investments to provide support for the supply chain's decision to reduce emissions under different market conditions. As shown in Fig. 11, the following conclusions can be drawn: (1) from the overall trend analysis, $\Pi_1^{M*} > \Pi_2^{M*} > \Pi_3^{M*}, \Pi_1^{S*} > \Pi_2^{S*} > \Pi_3^{r*} > \Pi_3^{d*}$. Among the three dual-channel models, model A has higher profits for supply chain members than the other channels. (2) For manufacturer profits, there is a peak profit point as the $t$ increases. This is similar to the findings of Wang et al. (2019), who argue that "given consumers' low-carbon preferences, there is an optimal level of emission reduction that maximizes the overall benefit of the supply chain." Among the three models, the level of $t$ at the peak point: model B > model A > model C. It indicates that the ratio of low-carbon gain to cost investment in the supply chain determines the initiative of manufacturers' emission reduction investment. (3) There are low-carbon investment parties and beneficiaries, and the investment level is influenced by the combined effect of cost investment and trust, while the beneficiary effect is related to the dual-channel model and the channel share. Regarding this conclusion, the research of He et al. (2018) also shows that the profits of supply chain members are not only related to their own input level and risk aversion but also related to the input level of other members.

The comparison of profit levels of three dual-channel models under different dual-channel parameters is analyzed, as shown in Fig. 12. The following conclusions can be

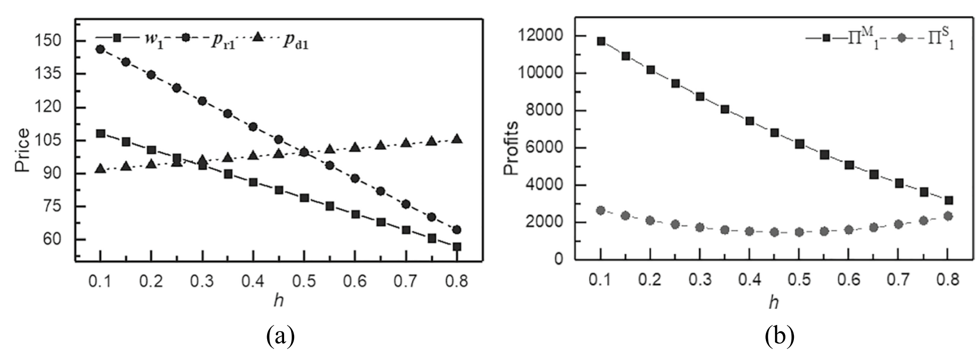



**Fig. 8** The effect of consumer channel preferences on the optimal decision of supply chain members (**a**) Impact of $h$ on pricing decisions; (**b**) Impact of $h$ on profits

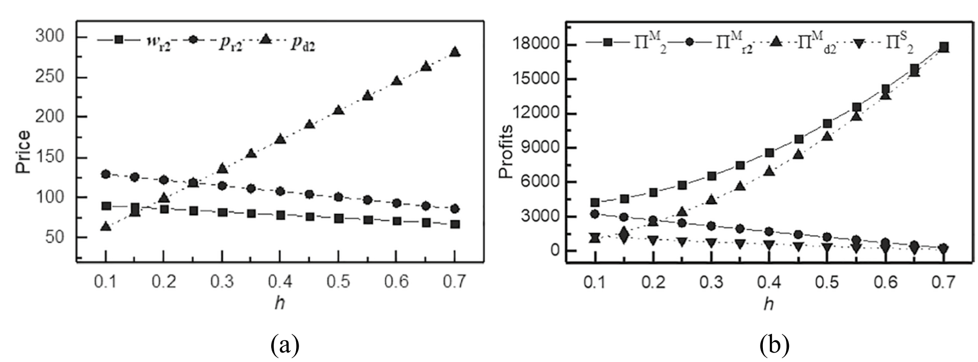



**Fig. 9** The influence of consumer channel preferences on manufacturers' decisions (**a**) Impact of $h$ on pricing decisions; (**b**) Impact of $h$ on profits

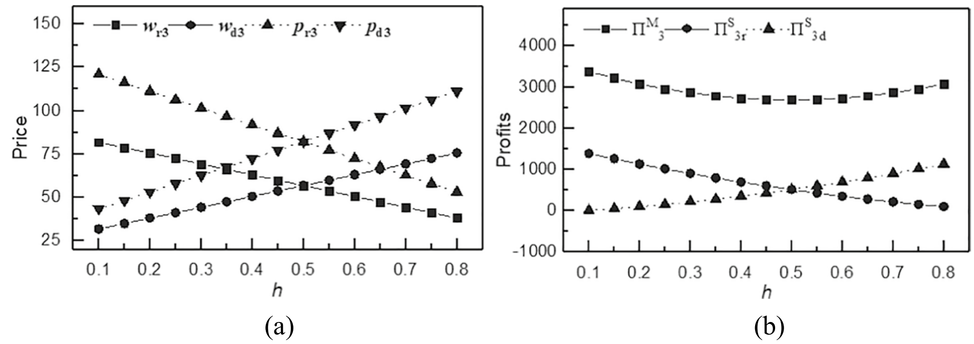



**Fig. 10** The impact of consumer channel preferences on retailers' online distribution decisions (**a**) Impact of $h$ on pricing decisions; (**b**) Impact of $h$ on profits

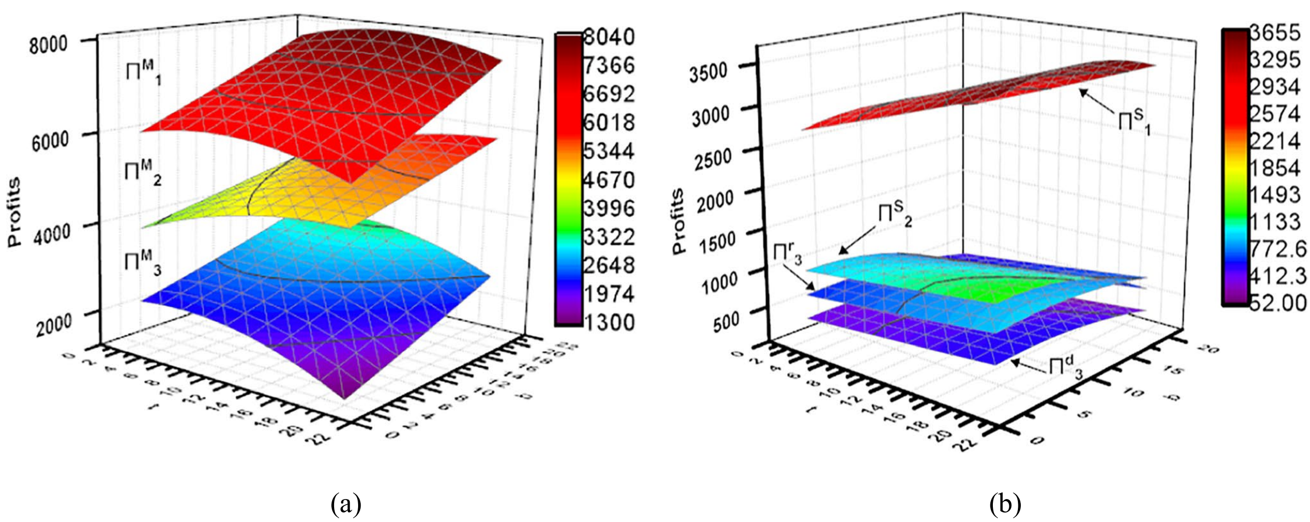
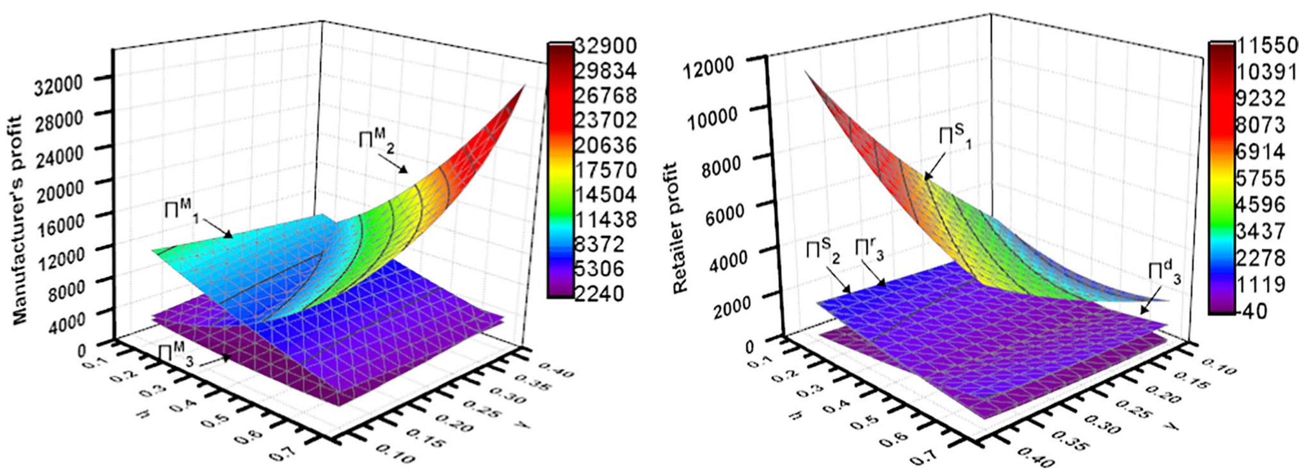



**Fig. 11** The interactive effect of emission reduction and blockchain investment on profit in three dual-channel models (**a**) The interactive effect on manufacturer profits; (**b**) The interactive effect on retailer and e-commerce profits

drawn: (1) With the change of parameters, there is a crossover in the trend of profit change of supply chain members, and the difference in the trend of change is obvious. (2) For manufacturer profit, the profit of model B has a positive correlation, while the speed of increase is significantly higher than others. For retailer and third-party e-commerce profits, the profit change for model A is significantly higher than others. (3) The system is less stable under high channel share difference $\Delta h$ and high price sensitivity coefficient $\gamma$, which can easily form extreme channel dominance. (4) The difference in change trends is due to the fact that the online channel is dominated by retailers, manufacturers, and third-party e-commerce under the three channels, respectively. $h$ and $\gamma$ increase will increase the share of online channels in the supply chain, and the profits of supply chain members dominating online channels increase significantly, which affects the profit level among members.

(2) Analysis of emission reduction levels under three dual-channel models.

As Fig. 13 shows the comparison of emission reduction levels of three dual-channel modes under different dual-channel parameters. It can be found that for emission reductions, $t_1$ decreases linearly and $t_2$ increases linearly as $h$ increases, while $t_3$ is not affected by the change of $h$. With the increase of $\gamma$, $t_1$, $t_2$, and $t_3$ emission reductions are accelerated. The following conclusions can be drawn: (1) The increase of $h$ and $\gamma$ will promote the market share of the online channel, while $t$ is driven by the manufacturer's profit, and the more the manufacturer's channel share, the higher the emission reduction tends to be. (2) In order to guarantee higher supply chain system emission reduction, the profit of both channels should be linked to the manufacturer to make greater $t$ through the profit drive. This is similar to the findings of Wang et al. (2018), who argue that "tighter cap-and-trade regulation and higher low-carbon preferences have both stimulated manufacturers to reduce carbon emissions in their production processes." (3) In order to make the low-carbon product market demand higher, retailers should be considered to invest more in blockchain technology. Regarding the cooperation among members, the research of Han




(a) (b)

**Fig. 12** The interaction effect of consumer channel preference and price sensitivity coefficient on profit in three dual-channel models (**a**) The interactive effect on manufacturer profits; (**b**) The interactive effect on retailer and e-commerce profits

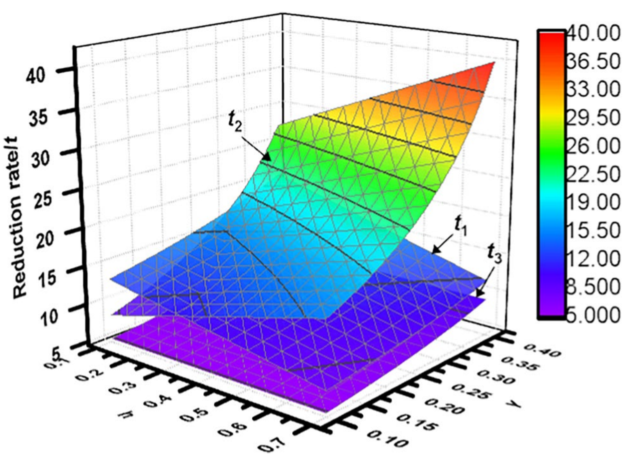



**Fig. 13** Interactive effects of consumer channel preferences and price sensitivity coefficients on carbon reduction in three dual-channel models

and Wang (2018) also shows that if the e-commerce platform can invest in technology or share the carbon emission reduction cost of manufacturers, the performance of the electronic supply chain will be greatly improved.

## Conclusion

In this study, based on the consideration that consumers have channel preferences and low-carbon sensitivity, a Stackelberg game model dominated by manufacturers was constructed to study the optimal decision of each member in the dual channels of a traditional retailer, manufacturer's online direct sales, and third-party e-commerce under the joint strategy of emission reduction investment and blockchain investment. Consumer channel preference, low-carbon sensitivity coefficient, price sensitivity coefficient, unit abatement volume, abatement cost coefficient, blockchain investment level, and blockchain cost coefficient were jointly introduced in the above three dual-channel structures to analyze the influence of the above parameters on manufacturers' channel selection and abatement strategy, aiming to provide a reference for channel selection and joint abatement strategy of supply chain members. Finally, the reasonableness and correctness of the obtained conclusions and propositions were verified by numerical simulation. The conclusions and management implications are as follows.

(1) In terms of profits of supply chain members, the optimal emission reduction of manufacturers and blockchain investment levels of retailers under different dual-channel models are different. For manufacturer profits, there is a peak profit point when the abatement cost factor is greater than a certain threshold. Meanwhile, there exists a specific blockchain investment threshold, and when the retailer propaganda cost coefficient is greater than this threshold, there is a peak in retailer profits. And emission reduction technology and blockchain technology have mutual benefits. And in the emission reduction decision-making process, there are the technology investment side and beneficiary side, and the level of investment is affected by the double gain effect of low-carbon emission reduction and trust and the combined effect of cost investment. Besides, the beneficiary effect is related to dual-channel modes and channel share. It indicates that the ratio of low-carbon gain to cost investment in the supply chain determines

the initiative of manufacturers' emission reduction investment and retailers' blockchain investment.

(2) The profits of supply chain members are obviously affected by the change in dual-channel parameters. With the increase of dual-channel parameters, there is a crossover in the changing trend of supply chain members' profit and the difference in the changing trend is obvious, which affects profit distribution among channels. Meanwhile, through the analysis, it is found that the difference in the changing trend is mainly due to the different leaders of the online channel under different dual-channel models. And the increase of $h$ and $\gamma$ will enhance the share of online channels in the supply chain and significantly increase the profit of supply chain members dominating online channels. Meanwhile, high channel share difference $\Delta h$ and high price sensitivity coefficient $\gamma$ will result in a crossover in system stability, which is easy to form extreme channel dominance. And it is not conducive to the long-term cooperation and development of members.

(3) In terms of dual channels selection, through the comparison of profits and emission reductions under the three channels, it is shown that when the same level of low-carbon investment is made, the profit of members under the traditional retail dual-channel model > manufacturer's online direct sales dual-channel model > third-party e-commerce distribution dual-channel model; in the process of changing channel parameters, the third-party e-commerce distribution channel model has checks and balances among multiple members and is least affected by channel changes; from the emission reduction perspective analysis, influenced by the manufacturer's channel share, the manufacturer's online direct sales dual-channel model > traditional retail dual-channel model > third-party e-commerce distribution dual-channel model. It can be found that the emission reduction investment is driven by the profit of the manufacturer. The more the emission reduction channel share of the manufacturer, the higher the emission reduction investment.

(4) In terms of emission reduction decision, there is an optimal emission reduction cost threshold, and when the emission reduction cost coefficient is greater than this certain threshold, optimal emission reduction can be achieved under the different dual-channel channel modes. Meanwhile, there are specific blockchain investment thresholds in different dual-channel modes, and the increase of the threshold value will improve the emission reduction. Therefore, considering that emissions reductions are driven by manufacturer profits, the profits of both channels should be linked to the manufacturer to secure higher supply chain system emission reductions, and greater emission reduction investment should be made through profit-driven. Retailers should be considered to increase blockchain investment to make higher market demand for low-carbon products.

The above findings have the following management implications for the channel selection and emission reduction strategies of dual-channel supply chains in a low-carbon environment: First, when manufacturers choose different dual-channel models, there are different optimal emission reductions to achieve optimal profits. And the best dual-channel model and emission reduction investment can be matched according to the market environment and reality. Second, the profit of traditional retailers can take advantage of offline physical stores, such as improving service levels, improving the consumer experience, and providing door-to-door services to gain a competitive advantage and thus increase profits. Third, low-carbon campaigns by retailers are beneficial to enhance profit levels and can increase the competitive advantage of the channel at the same time. Joint promotion models can be launched based on online direct sales and third-party distribution, and some promotion models can be used to attract consumers to purchase through online channels. Fourth, when dual-channel leaders formulate marketing strategies, on the one hand, emerging information technologies such as blockchain can be used to consolidate corporate image and increase corporate reputation. To drive the development of other channels, so as to form a spiral upward and alternate development, this kind of endogenous competition can greatly promote the internal self-innovation power of enterprises. At the same time, it will also bring a better experience to consumers and promote the healthy development of society.

## Limitations and future direction

However, this study only preliminary studies the optimal decision-making and emission reduction strategies of supply chain members under different channel structures and has not carried out the research on the coordinated decision-making of profit sharing and cost-sharing among members, which has limitations. Meanwhile, in the process of research on emission reduction strategies, the constraints such as carbon caps and carbon trading are not considered comprehensively, and follow-up research is required. In view of the limited dynamic analysis subjects in this paper, future research can start from the perspective of a multi-subject game, comprehensively considering the impact of carbon caps and carbon trading constraints on the joint emission reduction strategies of manufacturers and retailers so as to provide a comprehensive and optimized solution for the sustainable development of low-carbon products.

## Appendix

1. Proof of Theorem 1: Using Stackelberg's inverse induction method for the solution, substituting Eqs. (3) and (4) into the profit function (6) and taking partial derivatives of $p_{r1}$ and $p_{d1}$, respectively, we get $\frac{\partial \Pi_1^S}{\partial p_{r1}} = a(1-h) - 2p_{r1} + 2\gamma p_{d1} + (1-\gamma)w_1 + \eta t_1 + \delta b_1$, and $\frac{\partial \Pi_1^S}{\partial p_{d1}} = ah + 2\gamma p_{r1} - 2p_{d1} + (1-\gamma)w_1 + \eta t_1 + \delta b_1$; $\frac{\partial^2 \Pi_1^S}{\partial {p_{r1}}^2} = \frac{\partial^2 \Pi_1^S}{\partial {p_{d1}}^2} = -2 < 0$. Get the Hessian matrix $H\left(\Pi_1^S\right) = \begin{pmatrix} -2 & -2\gamma \\ -2\gamma & -2 \end{pmatrix}, 0 < \gamma < 1$ of $\Pi_1^S$ with respect to $p_{r1}$, $p_{d1}$, can determine H($\Pi_1^S$) as a negative definite matrix and get the optimal solution $p_{r1}^* = \frac{w_1}{2} + \frac{a(1-h+h\gamma)}{2(1-\gamma^2)} + \frac{1}{2(1-\gamma)}\left(\eta t_1 + \delta b_1\right)$, $p_{d1}^* = \frac{w_1}{2} + \frac{a(\gamma+h-h\gamma)}{2(1-\gamma^2)} + \frac{1}{2(1-\gamma)}(\eta t_1 + \delta b_1)$. Substituting the derived optimal solution ${p_{r1}}^*$ and ${p_{d1}}^*$ into the manufacturer's profit function (5), the derivative of $w_1$, i.e., $\frac{\partial \Pi_1^M}{\partial w_1} = -2(1-\gamma)w_1 + \frac{a(3-2h)}{2} + \eta t_1 + \delta b_1 = 0$, $\frac{\partial^2 \Pi_1^M}{\partial {w_1}^2} = -2(1-\gamma) < 0$, which is a convex function about $w_1$, which yields $\Pi_1^M$, which gives the optimal decision and the optimal profit.

2. Proof of Theorem 2: Substituting formula (14) into the profit function (17) and taking partial derivatives of $p_{r2}$, we get $\frac{\partial \Pi_2^S}{\partial p_{r2}} = \frac{a}{2}(1-h) - p_{r2} + \frac{\gamma}{2}p_{d2} + \frac{1}{2}w_2 + \frac{1}{2}\eta t_2 + \frac{1}{2}\delta b_2$, $\frac{\partial^2 \Pi_2^S}{\partial {p_{r2}}^2} = -1 < 0$ is a concave function on $p_{r2}$ of the concave function, the optimal solution ${p_{r2}}^*$ can be found. Substituting it into (16) and taking partial derivatives of $w_{r2}, p_{d2}$, respectively, we get $\frac{\partial \Pi_2^M}{\partial w_{r2}} = \frac{a(1-h)}{2} + \gamma p_{d2} - w_{r2} + \frac{1}{2}\eta t_2 + \frac{1}{2}\delta b_2$ and $\frac{\partial \Pi_2^M}{\partial p_{d2}} = \frac{a(-h\gamma+2h+\gamma)}{2} - \left(1-\gamma^2\right)p_{d2} + \gamma w_{r2} + \frac{2+\gamma}{2}\eta t_2 + \frac{\gamma}{2}\delta b_2$. The Hessian matrix $H\left(\Pi_2^M\right) = \begin{pmatrix} -1 & \gamma \\ \gamma & -\left(1-\gamma^2\right) \end{pmatrix}, 0 < \gamma < 1$ of $\Pi_1^S$ with respect to $w_{r2}, p_{d2}$, can determine H($\Pi_2^M$) as a negative definite matrix, and the optimal decision and optimal profit can be obtained.

**Author contribution** All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Jiang Yongchang and Liu Chang. The first draft of the manuscript was written by Liu Chang, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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**Data availability** The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval** Ethical approval was obtained from the School of Management of the Harbin University of Commerce.

**Consent to participate** All authors are informed and agree to participate.

**Consent for publication** All authors are informed and agree to publish.

**Competing interests** The authors declare no competing interests.

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